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FINAL PROJECT REPORT

APPLICATION OF HYDROGEN ASSISTED LEAN OPERATION TO BIOGAS FUELED RECIPROCATING ENGINES (BioHALO)

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Preface

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Application of Hydrogen Assisted Lean Operation to Biogas-Fueled Reciprocating Engines (BioHALO) is the final report for the BioHALO project (Grant Number PIR-02-001) conducted by TIAX LLC. The information from this project contributes to PIER's Renewable Energy Technologies Program.

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ABSTRACT

A biogas-fueled engine project was undertaken to demonstrate a new hydrogen-assisted operation technology that offers significant economic and environmental advantages over conventional NOx engines for landfill gas to electricity applications. The project was led by TIAX, with Hess Microgen providing valuable support during the project. This innovative technology enables utilization of hydrogen-enriched landfill gas (LFG), produced on site, to shift the operating point of gas engines to low engine-out NOx regimes which are otherwise not feasible. This technology provides an alternative to siloxane removal and selective catalytic reduction after treatment which is seen as prohibitively expensive. In the project, a Hess Microgen 75 kilowatt (kW) gas-fired engine cogeneration unit was installed at the TIAX engine test facility in Cambridge, Massachusetts. A series of scoping tests were performed on the installed engine/generator fueled with synthetic landfill gas and synthetic reformate prepared using bottled gases. The experimental setup was used to define optimum reformer and engine configuration, operating strategy, and process control that gave best emissions performance with acceptable process operation. Test results demonstrated that the gas engine could be operated for sustained periods at 100 percent excess air with engine-out NOx emissions at 0.11 pound per megawatt-hour. Based on the optimum process configuration, the reformer and engine interface conceptual design, and detailed design was completed.

Keywords: Nitrous oxide, biogas, landfill gas, selective reduction catalyst, TIAX

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EXECUTIVE SUMMARY

The biogas-fueled engine technology enables utilization of hydrogen-enriched landfill gas, produced on site, to shift the operating point of gas engines to low nitrous oxide (NOx) regimes which are otherwise not feasible. Using this technology, there is no need for a selective catalytic reduction system which can be quite costly and requires siloxane removal to prevent poisoning. The gas engines are conventional modern engines in many respects, except they are specially fitted with an upstream fuel reformer which produces up to 10 percent hydrogen in the modified landfill gas fuel mixture. In California, there are 310 active municipal landfill sites (1999 EPA inventory), of which 20 percent have power generating applications. Installations must meet criteria pollutant standards which are 0.5 pound NOx per megawatt-hour currently, and expected to be reduced to 0.1 pound per megawatt-hour by year 2012. There are hundreds of such reciprocating engine power-plants operating in the U.S. today on landfill gas, and the state-of-the-art low-NOx engines emit approximately 1.2 pound NOx per megawatt-hour. (See Section 1)

The objective of the demonstration was to prove that biogas hydrogen-assisted lean operation technology ("BioHALO") can be effective in lowering NOx to 0.1pound per megawatt hour by operating a retrofitted gas engine in a realistic landfill operating setting. The key accomplishments of the project can be summarized as follows: The team (1) designed, constructed, and installed a modified 75 kW, 10-cylinder Ford biogas engine at the TIAX engine test facility in preparation for the demonstration test (special engine parts and subsystems were fabricated which made the engine hydrogen-assist ready), (2) tested and optimized the BioHALO operating configuration for this engine using synthetic landfill gas and reformate gas mixed from gas cylinders and achieved low NOx levels of 0.11 pound/megawatt-hour, (3) designed a reformer subsystem to produce hydrogen from landfill gas with required heat exchangers and process controls, (4) separately designed the interface of the reformer to the engine with required start up sequencing, (5) conducted extended duration tests at the low NOx operating point at the TIAX test facility to demonstrate sustained operation, and (7) developed a planned path to market to commercialize the BioHALO technology.

In the project, a Hess Microgen 75 kW gas-fired engine cogeneration unit was installed at the TIAX engine test facility in Cambridge, Massachusetts. A parallel engine, reformer study was completed with a series of scoping tests performed on the installed engine/generator fueled with synthetic landfill gas. Synthetic reformate prepared using bottled gases was used in the tests. Next, the experimental setup was exercised in a series on concept optimization studies to define optimum reformer and engine configuration, operating strategy, and process control concept. The focus of these concept optimization studies was to find the process configuration and operational characteristics that give best emissions performance with acceptable process operation. These verification tests were also performed with synthetic reformate. Our definition of the optimum process configuration was adjusted based on verification test results.

Test results demonstrated that the gas engine could be operated for sustained periods at 100 percent excess air with engine-out NOx emissions at 0.11 pound per megawatt-hour. With the optimum process configuration defined, the authors proceeded with tasks to complete the reformer and engine interface conceptual design, and detailed design.

Based on the test results and design work performed in this project, the following target performance specifications of the mature commercial embodiment of the hydrogen-assisted engine appear to be feasible with further work. If achieved, this technology will be quite competitive:

- 34-38 percent efficiency
- $1000/kW installed cost
- Emission levels controlled to 0.1 pound per megawatt-hour NOx
- No requirement for selective catalytic reduction

After the project was well underway, the necessary commercial partners did not provide needed matching funds (and a host landfill gas site) to build the field installation and to operate the landfill gas engine facility on an actual landfill gas as opposed to synthetic simulated gas. Nevertheless a significant number of technical advances were made, and these are summarized in this report for the benefit of future landfill gas engine development efforts that are being planned to commercialize BioHALO for landfill-gas power production.

The project was led by TIAX, with Hess Microgen providing valuable support during the project.

1.0 Background and Objectives

1.1 Background -- Current Landfill Technology

The project reported here addresses landfill gas usage for electricity in a clean and cost effective manner. Municipal solid waste landfills generate a waste gas consisting of methane, carbon dioxide, and non-methane organic compounds. Because landfill non-methane organic compounds contribute to ambient level ozone concentrations, a federal New Source Performance Standard was promulgated in 1996. This standard requires larger landfills to collect and combust their gas; perhaps more worrisome than the landfill contribution to ambient ozone, is their significant greenhouse gas emissions. Landfills are the largest emitter of methane in the United States, accounting for 35 percent of all methane emissions in 1999[1]. While increased flaring of landfill gas will reduce emissions of methane, the flares generate nitrous oxide (NOx) and carbon dioxide (CO_2). Converting the landfill gas to electricity has the added benefit of displacing central station power plant NOx and CO_2 emissions.

The air quality management districts in California have adopted rules requiring many landfills to collect and "process" landfill gas. Most districts define "processing" as a 98 percent destruction of non-methane organic compounds. To date, most landfills have opted to simply flare their landfill gas. The California Energy Commission estimates that of the approximately 310 active municipal solid waste landfills, gas to electricity projects have been undertaken (in operation or planned) at approximately 60 of them. However many of these projects are held up by excessive NOx emissions of the prime movers, internal combustion engines or microturbines. It is expected that rules requiring collection and destruction of landfill gas will be more widely applicable in the future. At the same time, there is increasing pressure to reduce criteria pollutant emissions from landfill gas prime movers.

The ideal landfill gas prime mover should be efficient, have minimal NOx emissions, and be reasonably affordable. Higher efficiency units displace more fossil fuel generated electricity for a given amount of landfill gas. Since electricity generated at the landfill displaces central power plant electricity, criteria pollutant emissions (NOx, CO, volatile organic compound [VOC], particulates [PM_{10}] should be equivalent to or less than central station power plants on a pound/megawatt-hour (lb/MWh) basis. Finally, relatively low installed costs will result in more rapid and widespread conversion of landfill gas to electricity.

At present, there are two main options for conversion of landfill gas to electricity: the reciprocating internal combustion (IC) engine and the microturbine. The IC engine, because of its relatively high efficiency (28 to 38 percent) and low cost, is more prevalent. However, landfill-gas-fired IC engines suffer from relatively high NOx emissions. Microturbines can emit less NOx but are much less efficient (~23 percent) and up to three times more expensive. For fossil fuel applications, post-combustion catalytic reduction makes the IC engine NOx on a

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1 U.S. Department of State, U.S. Climate Action Report 2002, Washington, D.C., May 2002.

lb/MWh basis equivalent to that from a microturbine. In fact, the California Air Resources Board (ARB) guidance document recommends identical best available control technology (BACT) NOx levels for fossil-fuel-fired IC engines and microturbines[2], which are currently regulated at 0.07 lb NOx per MWh.

Fossil fuel fired IC engines achieve their lowest achievable NOx levels with either of two approaches: lean burn operation with ammonia-based selective catalytic reduction (SCR) or rich burn operation with a three-way catalyst (TWC). The lean burn approach is more efficient and typically yields lower NOx levels than the rich burn plus three-way catalyst approach (0.21 lb/MWh vs. 0.45 lb/MWh). However, the SCR system is considerably more expensive.

Table 1-1. Current and Proposed Waste-Gas Emission Standards for IC Engines

	IC Engine lb/MWh		
	NO_x	VOC	CO
September 2001 (Current)	1.9	1.9	7.8
January 2008 (Proposed)	0.5	1.0	6.0
January 2013 (Proposed)	0.07	0.02	0.10

Table 1-1 shows the ARB-recommended BACT levels for waste-gas-fired units as of September 2001. In 2007, ARB proposed in their 10-19-2006 Rulemaking a NOx level of 0.5 lb/MWh for certifying waste gas fueled IC Engines. The NOx BACT level for waste-gas-fired IC engines proposed for January 2008 is seven times higher than that for fossil-fuel-fired IC engines (natural gas). The Air Resources Board has recommended the higher landfill gas fired IC engine NOx levels as BACT for January 2008 because catalytic reduction techniques (TWC and SCR) are not presently feasible for waste-gas-fired engines. The catalysts in SCR and TWC systems are very sensitive to the presence of chlorine and chlorides, which react with both the ammonia added to the exhaust stream to form ammonium chloride and with the vanadium oxide in the catalyst, to form inactive vanadium chlorides[3]. In addition, siloxanes present in landfill gas (LFG) must be removed to prevent catalyst poisoning. Thus, the only NOx control technique available for IC engines firing waste gas is lean burn combustion.

The lowest NOx level from landfill-gas-fired IC engines has been achieved with a large (3 MW) lean burn Caterpillar engine equipped with a prechamber. Based on publicly available NOx source test data, this engine emits between 0.4 and 0.6 grams per break horsepower-hour

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2 *Guidance for the Permitting of Electrical Generation Technologies*, California Air Resources Board, September 2001.

3 Chen, J. P., Buzanowski, M. A., Yang, R. T., and Cichanowicz, J. E., *J. Air Waste Manage. Assoc.* 1990, *40*, 1403-9.

(g/bhp-hr[4]). The engine efficiency is approximately 36.7 percent, and it operates at twice the theoretical amount of air (lambda, the ratio of the actual amount of combustion air to the stoichiometric amount required to completely combust the fuel charge, of 2). The prechamber design allows for overall fuel lean combustion because the fuel is ignited with only a portion of the air in the prechamber. A lambda of 2 is close to the lean limit for prechamber engines, and therefore a NOx level of 0.4 g/bhp-hr represents a NOx emissions limit (barrier) for current technology landfill-gas-fired IC engines. Operationally, these engines suffer from heat losses due to the prechamber's high surface to volume ratio and the convective losses as the hot gases flow at high velocity through an orifice into the cylinder. These heat losses reduce cycle efficiency by three to four percentage points. Prechambers are also a high maintenance component.

Although achieving 0.4 g/bhp-hr (1.24 lb/MWh or 0.12 pounds per million British thermal unit (lb/MMBtu) at a heat rate of 10,600 Btu/kWh) is commendable for a waste gas fired IC engine, it is still significantly higher than the NOx emission rate from a central station power plant. Senate Bill 1298 (2000, Bowen) was intended to protect the environment should a significant number of distributed generation units be installed. SB 1298 requires that the BACT levels for distributed generation units must be reduced to the level of a central station power plant equipped with BACT at the earliest practicable date. ARB has defined BACT for central station power plants as 0.06 lb/MWh. The ARB standard for natural gas fueled IC Engines as of year 2007 is 0.07 lb/MWh. This represents a 95 percent reduction over what is currently achievable with a landfill gas fired IC engine and/or microturbine. Clearly, a significant barrier for landfill gas to electricity projects is the increasing downward pressure on emissions beyond what is currently possible. Because the market size is limited, there is little financial incentive for engine manufacturers and pollution control equipment vendors to address the waste gas fired IC engine NOx barrier.

This project leveraged the inherent high efficiency and low cost of lean burn IC engines by dramatically reducing NOx emissions from the achieved-in-practice level of 0.4 g/bhp-hr (1.24 lb/MWh or 0.12 lb/MMBtu) to 0.035 g/bhp-hr (0.11 lb/MWh or 0.011 lb/MMBtu). A best effort was made to achieve a 95 percent reduction down to the central station power plant level of 0.02 g/bhp-hr (0.06 lb/MWh). Some landfill applications will be suitable for combined heat and power (CHP) projects since hot water will be generated from the sensible heat in the engine exhaust. To encourage CHP projects, ARB has recommended that the process heat used be added to the power output in the denominator of the NOx emission factor calculation. For our BioHALO technology, taking credit for the 160,800 Btu/hr of hot water reduces the NOx from 0.11 lb/MWhr to 0.06 lb/MWh, identical to the BACT level for central station power plants.

The primary biomass resource the researchers' technology addresses is LFG. While this resource at existing closed landfills has a 20- to 30-year lifetime, LFG will continue to be available from active landfills for a more extended period. However, as more of the organic

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4 Srinivasan, K.K., et al. "The Advanced Injection Low Pilot Ignited Natural Gas Engine," *J. Eng. Gas Turbines and Power*, Vol. 128, p. 213, Jan 2006.

content of municipal waste is diverted from landfilling in response to state and local mandates, the quantity of LFG continuing to be produced will gradually decline. This represents a main strength of the BioHALO technology approach. Following this project, assuming TIAX teams with a landfill-to-power supplier, the authors expect to be able to demonstrate the BioHALO technology in the field within two years and commercialize the process shortly thereafter. Thus, the technology will be available while the LFG resource is still plentiful and will allow further exploitation of the resource using the most efficient and lowest cost means of generating electricity from LFG, the reciprocating IC engine-driven generator. The BioHALO technology can also be used with anaerobic digester gas at sewage and wastewater treatment plants, a biomass resource with longer lifetime, but presently produced in less significant quantities than LFG.

1.2 Overview of the BioHALO Approach

Reciprocating IC engines fueled with LFG have relatively high engine-out NOx emissions. The common approach to reducing high engine-out emissions from natural gas or propane fueled engines is to employ post-combustion catalytic NOx reduction. However, the use of catalysts is not feasible with LFG-fueled engines because LFG contains catalyst-inhibiting contaminants. Thus, it is necessary to reduce LFG engine emissions through in-cylinder combustion modifications. One of the best in-cylinder modifications is to employ lean combustion, (i.e., operate at high air-fuel ratios). However, there is a limit to how lean the engine can be operated imposed by the lean limit of stable combustion. This limit can be extended, though, by adding hydrogen to the fuel mixture. Thus, by employing BioHALO (hydrogen assisted lean operation), stable operation at very lean air-fuel ratios is possible, with attendant very low NOx emissions. This was the basis of the technology to be developed and demonstrated in this project.

Fractional hydrogen substitution in spark-ignited engines burning natural gas, liquefied petroleum gas or gasoline has been investigated by a number of researchers and has been demonstrated to offer a number of advantages, primarily as a result of increased laminar flame speeds. The primary advantage, as noted above, is the ability to offer stable combustion at much higher air to fuel (A/F) ratio, with associated substantial reductions on engine NOx emissions. Researchers' own engine modeling predictions and engine testing results show that 90 percent NOx emission reductions from the 0.4 g/bhp-hr BACT levels noted above are in fact achievable. The economic projections show that an engine/ generator equipped with the BioHALO technology will be able to be installed at a capital cost of less than $1,000/kW and have a simple payback of two to three years. Thus, the technology will be competitive.

1.3 Objectives

The technical performance objectives of this project were:

- Develop and demonstrate a landfill gas autothermal reformer with a 70 percent conversion efficiency. Conversion efficiency is defined as (H_2+CO) produced/CH_4 input to the reformer.
- Use the landfill gas reformate to reduce IC engine NOx emissions to 0.032 g/bhp-hr (0.10 lb/MWh) without the CHP credit. With the CHP credit, NOx emissions will be 0.02 g/bhp-hr (0.06 lb/MWh).
- Make a best effort to achieve the central station power plant best available control technology NOx level of 0.032 g/bhp-hr (0.1 lb/MWh) without the CHP credit.

The economic performance objectives of this project were:

- At production volumes of approximately 100 units per year, a reformer capital cost of \$300/kW (where kW is H_2 + CO thermal equivalent on an lower heating value (LHV) basis).
- Installed capital cost of commercial system less than \$1000 kW.
- Simple payback period less than three years.

Table 1-2 lists the agreement targets, most desirable goals, and estimated project performance objectives. For NOx emissions, the 0.032 g/bhp-hr target is shown converted to lb/MMBtu units. The VOC and CO goals include the use of an oxidation catalyst operating at approximately 85 percent efficiency. Oxidation catalysts are not prone to the poisoning that preclude the use of three-way and SCR NOx catalysts with landfill gas. The economic targets are for a 75 kW BioHALO IC engine system as described in Section 8 and Section 9. As can be seen, the BioHALO IC engine surpasses the stretch goal for affordability.

Table 1-2. Comparison of Agreement Targets and Stretch Goals to the Project Objectives

Target Parameter	Units	Agreement Target	Stretch Goal	Project
Air Emissions[a]				
NO_x	lb/MMBtu	0.01	0.0005	0.01
VOC	lb/MMBtu	0.007	0.001	0.007
CO	lb/MMBtu	0.10	0.002	0.09
Affordability[b]	\$/kWh	<0.06	<0.04	<0.03
Capital Cost[c]	\$/kW	<1,000	<500	900
Heat Rate[d]	Btu/kWh	<11,000	<8,000	10,000 6,017
Lifetime	Hr	>5,000	>10,000	>5,000
Capacity Factor	%	>90	>95	>90

[a] Converted NO_x goal (0.032 g/bhp-hr; 0.10 lb/MWh) to lb/MMBtu with heatrate of 10,000 Btu/kWh. VOC and CO values assume the use of an oxidation catalyst at approximately 85% efficiency.
[b] Assumes a 71 kW engine with 80% annual capacity factor. [c] Includes installation.
[d] Improved Heatrate value (6,017) includes credit for cogenerated hot water used by plant (CHP).

In the project, researchers installed a Hess Microgen 75 kW cogeneration unit at the TIAX engine test facility in Cambridge, MA. Researchers next completed a parallel engine and reformer study with a series of scoping tests. The scoping tests were performed on the installed engine/ generator fueled with synthetic LFG. Synthetic reformate prepared using bottled gases was used in the tests. Next, the experimental setup was exercised in a series on concept optimization studies to define optimum reformer and engine configuration, operating strategy, and process control concept. The focus of these concept optimization studies was to find the process configuration and operational characteristics that gave best emissions performance with acceptable process operation. These verification tests were performed with synthetic reformate. The authors definition of the optimum process configuration was adjusted based on verification test results. With the optimum process configuration defined, the reformer and engine interface conceptual design, and detailed design were completed.

The BioHALO IC engine surpassed the stretch goal for efficiency if the combined heat and power (CHP) credit is taken. The IC engine/generator provided by Hess Microgen is a cogeneration unit. The proposed project will provide only a portion of the hot water required by the demonstration host site, so if successful, larger units could be used at other future installations. Per the project proposal, a description of the CHP heatrate calculation is provided in the following:

- Engine Heat Rate = 10,000 Btu/kWh
- Engine Output = 71 kW
- Engine Firing Rate = (10,000 Btu/kWh) * (71 kW) = 710,000 Btu/hr
- Engine Exhaust Flowrate = 1,340 lb/hr
- Engine Exhaust Temperature = 572°F
- Heat Exchanger Exit Temperature = 72°F
- Energy Recovered = (1,340 lb/hr)*(0.24 Btu/lb-ºF)*(572-72)°F
  = (160,800 Btu/hr)/(3,412 Btu/kWh)
  = 47 kW
- CHP Efficiency = (710,000 Btu/hr) / (71 kW + 47 kW) = 6,017 Btu/kWh

1.4 Benefits of BioHALO

BioHALO benefits apply not only to landfill gas resources used for biogas-to-electricity, but also apply broadly to all forms of biomass-to-energy in California. Based on the Energy Commission Report *Biomass in California: Challenges, Opportunities, and Potential for Sustainable Management* *and Development* (June 2005), the three primary sources of biomass for energy are agriculture, forestry, and municipal wastes. Of the 81 million gross tons of biomass produced annually, it is feasible to collect and use about 32 million tons for renewable electricity, biofuels, and biobased products. This is in addition to landfill biogas and wastewater treatment biogas. Currently, only about 5 million tons per year (16%) is used, in part because of the need for lower NOx engine-generator technology such as BioHALO. Biomass currently provides an estimated 975 MW of generating capacity in California (2%) alone, of which 305 MW is landfill gas generation capacity (in place and planned). As reported by EPA and DOE, several other states have significant landfill gas and other biomass-derived syngas to electricity potential. The benefits of BioHALO could be extended to anerobic digestion of dairy waste, food waste, waste water and other organic waste. Producer gas from thermal gasification of biomass is another source for BioHALO engine technology applications. Clearly there is enough resource to multiply this figure by a factor of five, and the BioHALO technology when commercialized could speed up the installation of the additional 5000 MW (for illustration think of 2500 BioHALO engines, each 2000 kW). This is not beyond the realm of feasibility because GE Jenbacher recently announced a single landfill installation in Europe with 60 engines (bringing the engine total to 560 engines sold) in Diesel & Gas Turbine Worldwide (January 2007).

Landfill operators need the type of technology we are proposing to develop and demonstrate to give them a near-term, cost-effective option to continuing to flaring LFG. The authors proposed technology can be readily integrated into the workhorse process for generating electricity from LFG and overcomes the major public objection to this approach, high NOx emissions. Our approach is unique in that it makes use of the LFG already in place to achieve the NOx reduction benefit achieved.

Just from landfill applications, the public benefits to be provided in California if the technology is successful and are incorporated into commercial IC engine driven generators include displacement of central station power, or creation of new generating capacity at lower cost, with annual public savings of $12M in power costs (based on a cost savings of $0.06/kW-hr); reduction in total greenhouse gas loading to the state of 0.9 Million tons/yr of CO_2 equivalent, with annual cost equivalent savings (at $25/ton GHG) of $22M; and reduction in NOx emissions from landfills previously using higher emission IC engines or turbines, or using flaring. These benefits could be realized within a year of project completion, with no additional public funding required. Considering all other biomass fuel sources the above numbers are tripled.

2.0 BioHALO Process Description and Technical Issues Addressed

2.1 Description of BioHALO Process

Despite its technical success, the HALO concept for ordinary natural gas IC engines (not LFG) has not found a viable commercial application in fossil-fuel-fired engines because three-way catalysts are also relatively inexpensive and provide low enough NOx emissions to meet current BACT requirements. Because SCR catalysts are not an affordable option for LFG engines, the proposal team believes that BioHALO is the least cost, lowest emitting, and fastest to market approach for LFG to electricity projects. However, there have been no demonstration projects for the BioHALO concept on landfill gas. A demonstration is the next necessary step to providing BioHALO as a viable near term NOx control option for LFG fired IC engines.

The BioHALO technology uses an autothermal reformer (ATR) to generate hydrogen and CO from the landfill gas. Specifically, the BioHALO system includes the following:

- LFG Engine typically 75 kW to 1500 kW operated at 100% excess air (10% O_2 in exhaust) with high energy ignition system.
- Engine turbocharged to at least 0.5 bar intake manifold above atmospheric, and aftercooled to maximum intake manifold temperature 40°C.
- Landfill gas reformer sized to supply hydrogen at 10% of the methane flow rate by energy (33% by volume H_2 in total H_2 plus CH_4). This implies that approximately 15% of the LFG flow is diverted to the reformer to produce hydrogen. (The reformer also produces CO fuel value at 22% volume CO per volume of hydrogen; therefore the fuel value of the CO adds 26% to the H_2 fuel value).
- System efficiency accounting for reformer thermal management must be within 2% of baseline without BioHALO.
- Auto-thermal reformer operating at equivalence ratio 3:1 (200% excess fuel). This reformer can be designed around a low cost catalyst similar to an automotive three-way catalyst, and is slightly exothermic (adiabatic temperature rise of about 200°C between inlet and outlet). For catalyst light off, the inlet gases must be at 600°C.
- *Need to cool down the reformate fuel gases:* The reformate gas (H_2, CO and inerts) exits the reformer at about 800°C and must be cooled down to about 140°C before remixing with the 85% main stream of LFG fuel. Otherwise air breathing would be impacted and engine power would suffer.
- *Need for preheat and sources of preheat:* Three gas inlet streams must be preheated in order to enter the reformer at 600°C (about 1100°F); the LFG itself, the water vapor (steam) required, and the air supply to the reformer.
- The exhaust gas exits the turbocharger intercooler at about 550°F (250°C) and still contains about 14% of the original fuel energy. Therefore exhaust gas can be used to (a) preheat

water to 100°C before creating steam for the reformer, (b) partially preheat the air to the reformer, say up to 200°C, and (c) preheat the LFG slipsteam up to 200°C.

- Hot reformate gas must be cooled and intake gases are available to provide cooling. The design assumes that a counter-flow heat exchanger is used.
- *Need LFG Burner for start up:* A small burner provides steam and preheats the reformer catalyst to light-off temperature

As shown in Figure 2-1, the reformate gas (H_2, CO, CO_2, and N_2) will be injected into the combustion air upstream of the turbocharger. For natural gas, existing TIAX data indicate that the NOx target can be achieved at a lambda of 2.1 (see Figure 2-2). For stable operation at this high lambda, approximately 10-15 percentage of the fuel (LHV basis) must be reformate. For the landfill gas application, the same percent fuel must come from the reformate, but the lambda can be reduced to approximately 1.8 because of the large amount of diluent provided by the landfill gas itself.

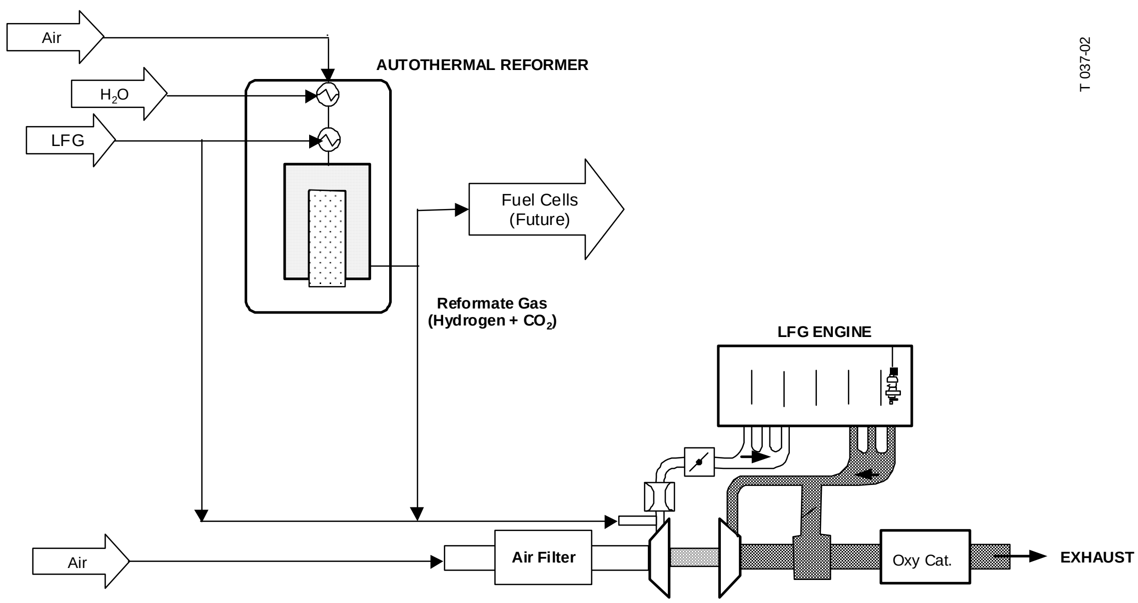

Figure 2-1. Process Flow Schematic of the Proposed TIAX BioHALO Landfill Gas Engine

The main technical advances that are expected if the proposed technology is commercialized are twofold. First, testing the BioHALO concept on an LFG IC engine in the field will definitively show whether reciprocating IC engines can/should be installed at landfills in the future. The other contribution from this project was advancement of knowledge in LFG reforming. Technical advancements made now in the low-cost production of hydrogen from LFG will be very advantageous in the future when fuel cell technology becomes economically competitive. One can envision LFG reformers providing reformate to IC engines generating electricity and providing hydrogen to fuel cell-powered garbage trucks.

2.2 Technical Issues Addressed

These challenges that were addressed in this project are listed below:

- To achieve the target levels of NOx, the LFG engine had to be operated considerably lean. Natural gas engines have to be operated at a lambda of 2.1 to achieve the target levels of NOx emissions. By itself, at this level of dilution, stable combustion will not be supported. However, augmented by hydrogen, at nominally 10 percent of the total heat input to the engine, the engine can be operated at a lambda of 2.1. A key risk to this technology was the ability of the engine to run with LFG at this high level of dilution. Our preliminary modeling efforts showed that for a nominal hydrogen input of 7 percent, the same level of dilution can be achieved with LFG, but for a lower lambda (around lambda = 1.8). As shown in Figure 2-2, the model results indicated that for a hydrogen input of 6.75 percent, the same amount of diluent is required to sustain stable combustion and achieve the target NOx, however, the amount of air required is significantly smaller. This is possible because of the large amount of CO_2 present in the LFG that acts as a diluent. Actual scoping tests that were performed during tasks 2.2 and 2.3 of this project confirmed the operability of the engine with LFG at high levels of dilution.

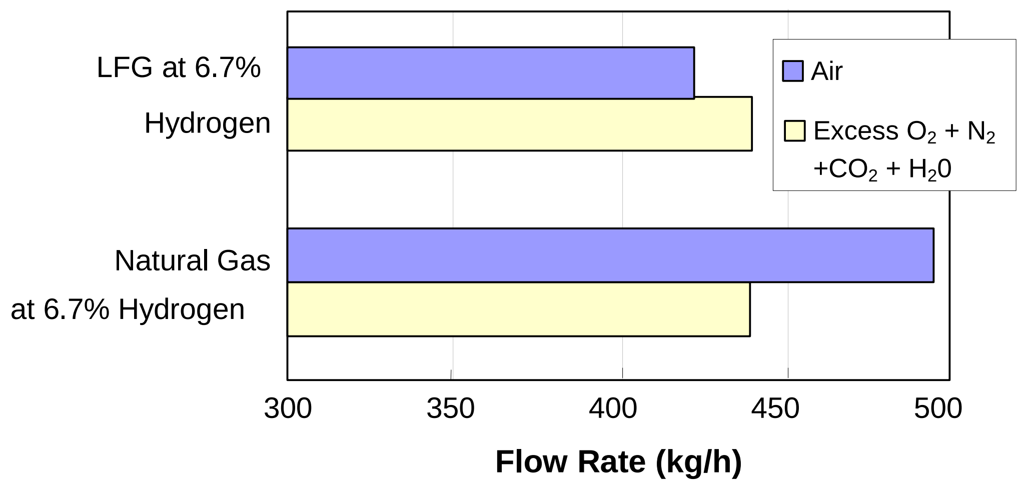

Figure 2-2. Air Requirements and Resulting Diluent for BioHALO, Operation With LFG and Natural Gas for a 75 kW Engine/Generator

- The very wide flammability limit of hydrogen, which is being taken advantage of in the HALO concept, also posed some inherent safety risks. One important consideration is the danger of pre-ignition of the hydrogen-LFG-air mixture in the intake manifold of the engine. Temperature and other activated components within the manifold could trigger the pre-ignition of the fuel mixture. However, previous studies by TIAX have shown that, at the high levels of dilution (see Item 1 above), the probability of pre-ignition of the fuel mixture is very low. The testing protocol used in this project established a safe operating envelope, mainly through the modeling efforts.

- Another important factor that is key to successful commercialization of BioHALO is the ATR to produce hydrogen-rich reformate from LFG. As is well known, LFG contains small amounts of sulfur and siloxane that can prove to be deleterious to reformer catalysts. This has been a common problem to the application of this technology since costly gas clean-up systems are required upstream of the reactor.
- Another factor that posed significant challenge to the program is also related to the operation of the ATR. The design had to provide preheat so that the large amounts of CO_2 in the LFG would still allow the ATR to achieve optimal temperature. The ATR system was designed to preheat the air with the exhaust from the LFG engine, thereby also increasing the overall efficiency of the system. The ATR design is flexible enough to allow for additional heat recovery to raise the inlet temperature of the ATR reactants. Waste heat from the LFG engine exhaust was also used to preheat the reactants that are needed for complete conversion to hydrogen and CO in the ATR.

The technical goal of the project was to demonstrate the feasibility of the BioHALO system as applied to landfill gas. To overcome the barrier to continued IC engine use in LFG to electricity projects, the authors have developed and demonstrated the use of hydrogen assisted lean operation (BioHALO) with simulated hydrogen production from LFG using autothermal reformer technology (BioHALO). This technology relies on the ability of hydrogen to extend the flammability limit for the stable combustion of methane to leaner air/fuel (A/F) ratios. Thus, while current technology operates at the lean flammability limit to achieve the above NOx emission levels, the BioHALO technology will allow even leaner operation to achieve a significant further NOx reduction. In this approach, a portion of the LFG fuel supply for the engine was fed to an onsite autothermal reformer that will produce a hydrogen-rich reformate, which will be combined with the engine combustion air, thereby allowing hydrogen to enrich the air/fuel charge.

2.3 NOx Emissions From Internal Combustion Engines

The project addressed several challenging issues related to power generation from landfill gas (LFG) or other biogas. Operating an internal combustion engine (ICE) on LFG precludes conventional emission control approaches because of contaminants in the gas that would poison catalysts. Very lean engine operation is one technique for achieving low NOx emissions; however, the low flame speed of methane limits the extent of lean operation.

The project resulted in the operation of an IC engine on LFG with very low emissions. The engine was operated on biogas in the Hydrogen-Assisted Lean Operation (BioHALO) configuration with onsite hydrogen generation. This section describes the challenges associated with emission reductions from IC engines and hydrogen production from LFG. BioHALO is directed at the central challenge of ultra-lean burn engines – repeatable, controlled, and complete combustion at very lean mixture ratios.

2.3.1. Engine-Out Emissions Level Is Critical for Landfill Gas Engines

Engine operating conditions and the extent of emission controls govern NOx emissions from gaseous-fueled engines. These emission levels affect where engines can be permitted for continuous operation. The authors' review of natural gas engine emissions and the recently published California Air Resources Board (ARB) Best Available Control Technology (BACT) Guidance Document, combined with interviews of engine distributors, shows that market potential of LFG engines for power generation is limited by their ability to achieve low NOx emissions.

Table 2-1 shows different configurations for IC engines and how the emissions are affected by emission controls. Both three-way catalyst (TWC) and selective catalytic reduction (SCR) can achieve very low NOx emissions. However, operating engines on LFG presents additional challenges. LFG has a lower energy content than natural gas, and it contains contaminants such as chlorinated hydrocarbons, sulfur compounds, and siloxanes (silicon compounds). These components tend to make conventional emission control approaches impractical. Sulfur, siloxanes, and chlorinated compounds will affect both the performance effectiveness and the life of both TWC and SCR catalysts. Since removing contaminants from LFG is costly and generates waste disposal problems, engine modifications appear to be the optimal approach for achieving low emissions from LFG engines.

Table 2-1. Effect of Emission Controls on NO_x Emissions From IC Engines

Engine Operation	Emission Control	Impact on Emissions	NO_x (g/bhp-hr)
Stoichiometric	None	Highest NO_x emissions	8
Stoichiometric	Three-way catalyst	NO_x reacts with CO and HC on catalyst	0.15
Lean burn, prechamber	None	Lower combustion temperatures, less NO_x	0.4
Lean burn	SCR (not feasible for LFG)	NO_x reacts on SCR catalyst in the presence of injected ammonia	0.05 to 0.15
Lean burn with hydrogen	None	Hydrogen in fuel extends lean operating limit	0.032 to 0.10

2.3.2. Lean-Burn Provides Ultra-Low Engine-Out NO_x and High Efficiency

The concept of ultra-lean-burn IC engines is one that engine manufacturers have been pursuing for a long time. It is well-known and documented that lean-burn operation offers several valuable advantages, such as increased ratio of specific heats over the expansion stroke, less dissociation, reduced cooling losses, and reduced throttling losses. Over the years it has been well-documented that lean burn reduces NOx and CO emissions while increasing engine thermal efficiency.

The formation of NOx emissions in spark ignition engines is primarily controlled by two parameters: in-cylinder peak gas temperature and in-cylinder oxygen concentration. Both of these parameters are affected by the air-fuel (A/F) ratio. For any fixed engine power setting, the in-cylinder gas temperature peaks at a slightly rich A/F-ratio (fuel equivalence ratio, $\phi \approx 1.1$). However at rich conditions the oxygen concentration is low, resulting in low NOx emissions. As the A/F-ratio is progressively made leaner, the oxygen concentration increases and the in-cylinder peak gas temperature falls off. Initially, the increasing oxygen concentration offsets the falling gas temperature resulting in maximum NOx emissions at an A/F-ratio slightly lean of stoichiometric ($\phi \approx 0.9$). As the A/F ratio becomes leaner ($\phi < 0.9$), the temperature effect dominates over the stoichiometry effect and NOx emissions decrease to very low levels at ultra-lean mixtures ($\phi < 0.5$).

2.3.3. Lean-Burn — Technical Challenges

A critical challenge in realizing practical lean-burn systems is that as the A/F ratio is increased, combustion becomes unstable before NOx and CO emissions are reduced significantly. Consequently, to be successful, sufficiently lean conditions must be achieved (equivalence ratio less than 0.5) such that stable combustion occurs with engine-out NOx and CO emissions at the very low levels necessary for the intended applications. Over the years, the ultra-lean-burn problem has been widely studied and reported in the literature. As a result, a number of approaches to achieve ultra-lean-burn have been suggested.

Historically, lean-burn has been pursued by increasing the level of turbulence in the combustion chamber (typically by mechanical vortex generators in the intake port and/or piston). The idea is to accelerate the burn rate through turbulence (increased thermal and mass diffusion and increased flame area by flame wrinkling and stretch) and thereby extend the lean limit for stable combustion. A problem with the high turbulence approach, however, is that the initial flame kernel generated by the ignition spark can be quenched by the increased thermal diffusivity and flame stretch, resulting in misfires. Therefore, special high-energy ignition sources are typically required to generate a relatively large initial flame. Unfortunately, high-energy ignition systems tend to aggravate spark plug erosion, resulting in more frequent spark plug replacement and higher maintenance costs. Moderate lean-burn has been successfully demonstrated with high turbulence/high energy ignition concepts. However, when one approaches ultra-lean operation (which is required for near-zero engine-out NOx emissions), partial burn and misfires are frequently encountered, resulting in excessive emissions of unburned hydrocarbons and poor thermal efficiency.

An alternative approach that has been pursued by many engine manufacturers is to use two combustion chambers. One called a torch chamber, jet cell™, or pre-chamber, contains a near-stoichiometric (or even rich) mixture that is ignited by conventional spark ignition. This pre-chamber is connected via a short passage to the other main chamber that contains the bulk, lean mixture. As a result of combustion generated pressure rise in the pre-chamber, a jet plume of hot burning gas is injected into the main chamber lean mixture. This hot jet serves as a powerful ignition source and turbulence generator, promoting fast burn of the lean bulk charge.

Prechamber systems can achieve very lean overall operation ($\phi \approx 0.5$). However, the prechamber technology has inherently higher NOx than a homogeneous charge lean configuration. While the rich zone in the prechamber enables overall lean combustion, it is a hot, near-stoichiometric zone that promotes NOx formation. As a consequence, emissions from lean-burn engines with prechambers are typically no lower than 0.4 g/bhp-hr because the prechamber results in NOx formation.

2.3.4. Hydrogen Assisted Operation Addresses the Central Challenges of Lean-burn

An effective alternative approach to accelerate the burn rate of ultra lean mixtures and thereby extend the lean operating limit is to utilize hydrogen as a supplement to conventional fossil hydrocarbon fuels. Fractional hydrogen substitution in spark ignited engines burning natural gas, liquefied petroleum gas, or gasoline has been investigated by a number of researchers[5,6,7,8,9,10,11,12,13,14] and have been demonstrated to offer a number of advantages, primarily as a result of increased laminar flame speeds. Key advantages include;

- Operation at very lean mixtures.
- Enhanced combustion stability.
- Increased thermal efficiency.
- Potential for ultra-low NOx emissions but increased HC emissions, depending on equivalence ratio.

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[5] Apostolescu, N., and Chiriac,R., "A Study of Hydrogen-Enriched Gasoline in a Spark Ignition Engine," SAE Paper No. 960603, in *Advances in Engine Combustion and Flow Diagnostics*, SP1157, 1996.

[6] Rauckis, M. J., and McLean,W. J., "The Effect of Hydrogen Addition on Ignition Delays and Flame Propagation in Spark Ignition Engines," *Combustion Science and Technology*, 19, pp. 207-216, 1979.

[7] Houseman, J., and Hoehn,F. W., "A Two-Charge Engine Concept: Hydrogen Enrichment," SAE Paper No. 741169, 1974.

[8] Stebar, R. F., and Parks,F. B., "Emission Control with Lean Operation Using Hydrogen-Supplemented Fuel," SAE Paper No. 740187, 1974.

[9] Lucas, G. G., and Richards,W. L., "The Hydrogen / Petrol Engine - The Means to Give Good Part Load Fuel Economy," SAE Paper No. 820315, 1982.

[10] Newkirk, M. S., and Abel,J. L., "The Boston Reformed Fuel Car," SAE Paper No. 720670, 1972.

[11] Jamal, Y., and Wyszynski,M. L., "On-Board Generation of Hydrogen-Rich Gaseous Fuels," *International Journal of Hydrogen Energy*, 19, No. 7, pp. 557-572, 1994.

[12] Swain, M. R., Yusuf, M. J.,Dulger, Z., and Swain, M. N., "The Effects of Hydrogen Addition on Natural Gas Engine Operation," 1993 SAE Transactions, Section 4, Paper No. 932775, 1993.

[13] Timoney, D. J., and Wilson, R. P., "Use Of Supplemental Hydrogen In Spark Ignition Engines: Simulation of Impact on Performance & Emissions," ISATA Technical Paper No. 98EL016, 1998.

[14] Timoney, D. J., Linna J. R., and Wilson, R. P., "Some Measured And Simulated Effects Of Supplemental Hydrogen In A Gasoline Engine," ISATA Technical Paper No. 00ELE036, 2000.

Negative influences arise from reduced volumetric efficiency (due to displacement of air) and decreased maximum power output.

LFG engines with prechambers can achieve NOx levels of 0.4 g/bhp-hr if the engine is operated at a relative air/fuel ratio (lambda) of 2. The lean limit for natural gas combustion with a homogeneous charge engine typically occurs at a lambda of 1.6 ($\phi \approx 0.6$), which is not lean enough for NOx emissions to reach ultra low levels. Since the homogeneous charge BioHALO approach eliminates the hot, near stoichiometric NOx promoting prechamber, the homogenous charge BioHALO engine can achieve lower NOx emissions at an equivalent lambda. Based on our testing of a simulated reformate/LFG fueled engine (see Chapter 6), a lambda of 2 will achieve 0.035 g/bhp-hr (0.011 lb/MMBtu). In the future, perhaps a slightly leaner engine configuration will result in NOx levels of 0.02 g/bhp-hr that is as low as the levels from new central station power plants equipped with BACT.

A comparison between emissions from a prechamber and homogeneous charge engine is illustrated in Figure 2-3. The addition of hydrogen allows the homogeneous charge engine to operate without misfire at lambda values up to 2.5 where NOx is virtually eliminated. The authors' modeling results show that NOx levels drop rapidly as the engine runs leaner. The lean operation is enabled with the addition of hydrogen. The higher flame speed of hydrogen allows the initial combustion in the cylinder to propagate faster and allows for engine operation without misfire. The authors' modeling combined with laboratory engine testing indicates that 6.75 percent of the total heat input from hydrogen allows for lean operation to a lambda of 2.

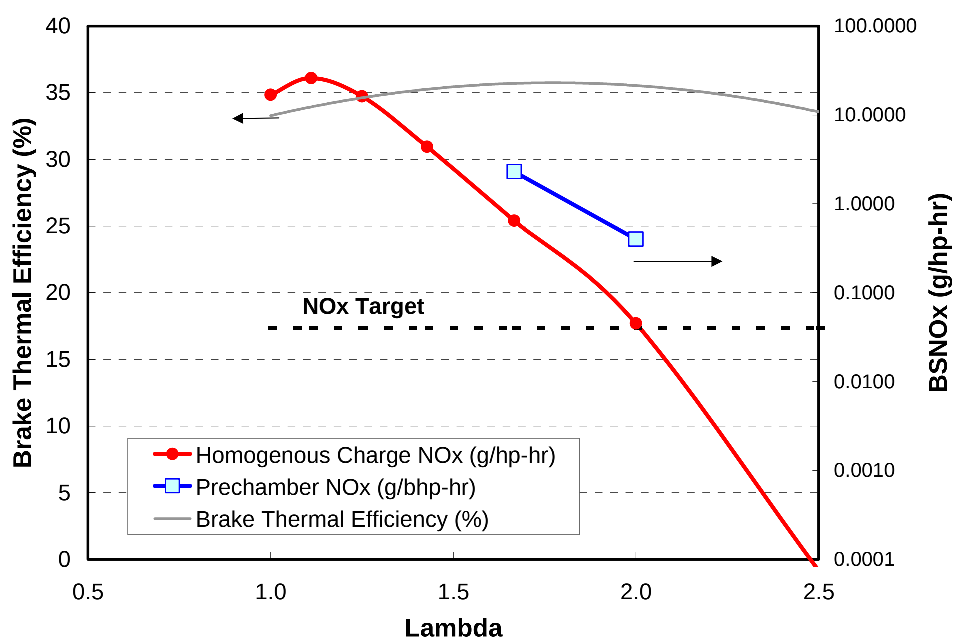

Figure 2-3. Emissions From IC Engines Vary With Air/Fuel Ratio

A critical challenge in the practical development of systems to provide hydrogen as fuel additive is supplying hydrogen. On-site storage of hydrogen is generally costly, not only the cost of hydrogen itself but also the cost of the special storage device. In addition, there exists no pipeline distribution infrastructure for hydrogen supply to engines. Therefore, on-site production of hydrogen or a hydrogen-containing gas is considered to have the greatest potential for commercialization. However, like any other component, an on-site system for hydrogen production must meet a number of requirements to be commercially viable. Requirements include:

- **Safety.** Components and systems need to be inherently safe and new or substitute components must not add further safety risks. Hydrogen calls for special consideration due to wide flammability limits, low net ignition energy in air, high flame speed, high heating value, and intrinsic propensity to leak.
- **Low Cost.** The reciprocating engine market is mature and very competitive. New concepts must be lower cost than competing technologies that meet the same objectives.
- **Size and Weight.** Added size and weight must be minimized. The industry is striving for higher output from smaller packages that will allow them to cut cost and lower unit prices.
- **Reliability.** Reliability is critical for keeping maintenance costs at a minimum. The average period of unit replacement for reciprocating engine generator sets falls in the 2-10 year range, and the trend is to require as many components and sub-systems as possible to last the service life of the engine without maintenance.

On-site fuel reforming using an auto-thermal reformer to produce a hydrogen-rich gaseous fuel stream has emerged as an attractive approach with a high probability of meeting these requirements. The auto-thermal reactor is an inherently simple device with no moving parts and does not require maintenance. It is easy to manufacture, uses conventional materials, and does not require close tolerance internal components. When integrated with the engine's fuel system, it would enjoy the same degree of safety as a modern fuel injection system – there is one connection to the fuel line, and the reactor outlet is ducted directly to the intake system.

2.4 Hydrogen Production and Reformers

A variety of reformer technologies have been used to convert hydrocarbons to hydrogen. These include steam reformers, partial oxidation with oxygen or air, and catalytic autothermal reforming. Steam reformers generally produce more moles of hydrogen per mole of hydrocarbon; however, they are difficult to design for small-scale applications, and the reforming catalysts are easily poisoned by sulfur, siloxanes, and other contaminants in the LFG. Catalytic autothermal reformers (ATRs), using the H_2fuel catalyst technology, are sulfur-tolerant and operate with a high hydrogen yield because of the integrated preheat of the reformer.

Autothermal reformers combine the heat effects of the partial oxidation and steam reforming reactions by feeding the fuel, water, and an oxidant such as air together into the reformer. This process is carried out in the presence of a catalyst, which controls the reaction pathways and thereby determines the relative extents of the oxidation and steam reforming reactions. The presence of steam and the use of an appropriate catalyst provide benefits, such as lower temperature operation and greater product selectivity to favor the formation of H_2 and CO, while inhibiting the formation of coke.

The initial oxidation reaction results in heat generation and high temperatures. The heat generated from the oxidation reaction is then used to steam-reform the remaining fuel by injecting an appropriate amount of steam into this gas mixture. The oxidation step in air may be conducted with or without a catalyst. The overall autothermal reforming reaction can be expressed as:

$$C_nH_mO_p + \chi(O_2 + 3.76N_2) + (2n - 2\chi - p)H_2O \Leftrightarrow (n-y)CO_2 + \left(2n - 2\chi - p + \frac{m}{2} - y\right)H_2 + yCO + yH_2O + 3.76\chi N_2$$

Where χ is the oxygen-to-fuel molar ratio and y is the number of moles of CO_2 that reacts with H_2 to produce CO and H_2O due to the reverse water gas shift (WGS) reaction.

This χ ratio is a very important parameter because it determines:

- The amount of water required to convert the carbon to carbon oxides.
- The hydrogen yield (moles).
- The concentration (mol%) of hydrogen in the products.
- The heat of reaction.

This reaction is endothermic at low values of χ, and exothermic at high values of χ. At an intermediate value (χ_o), the heat of reaction is zero.

For autothermal reforming of methane, n=1, m=4, p=0, and the overall reaction is given by:

$$CH_4 + \chi(O_2 + 3.76N_2) + (2 - 2\chi)H_2O \Leftrightarrow (1-y)CO_2 + (4 - 2\chi - y)H_2 + yCO + yH_2O + 3.76\chi N_2$$

When χ = 0.5 and y=0 (pure steam reforming)

$$CH_4 + 0.5(O_2 + 3.76N_2) + H_2O \Leftrightarrow CO_2 + 3H_2 + 1.88N_2$$

If y=0.5, then

$$CH_4 + 0.5(O_2 + 3.76N_2) + 0.5H_2O \Leftrightarrow 0.5CO_2 + 2.5H_2 + 0.5CO + 1.88N_2$$

If y=1 (pure partial oxidation or "POx"), then

$$CH_4 + 0.5(O_2 + 3.76N_2) \Leftrightarrow 2H_2 + CO + 1.88N_2$$

For each of these cases, the reformate gas has the composition given in Table 2-2.

Table 2-2. Product Gas Composition from Reformers

Reformer Products	mol %, dry, χ = 0.5		
	Pure Steam Reforming y=0	y=0.5	Pure POx y=1
H_2	51.0	46.5	41.0
CO	trace	9.3	20.5
CO_2	17.0	9.3	—
N_2	32.0	34.9	38.5
Total	100.0	100.0	100.0

Pure steam reforming (y=0) gives the highest H_2 yield, and pure partial oxidation reforming (y=1) gives the lowest. Regardless of the type of reformer, the initial product invariably contains at least a trace of carbon monoxide, i.e., y>0. The bulk of the CO can be converted to additional hydrogen via a separate WGS reaction that is typically done for hydrogen production systems. For the BioHALO system, the WGS can be eliminated because CO also burns with a high flame speed and helps support lean operation.

The effect of air and operating temperatures is illustrated in Figure 2-4. (For LFG, χ=2 corresponds to a reformer operation stoichiometric air fuel ratio [λ=1]). At low lambda values solid carbon or coke can form and the conversion of methane is low. Higher methane conversions can be achieved by operating at a leaner condition; however as more air is added to the reformer, more CO_2 and less hydrogen are produced. An alternative is to preheat the fuel, air, and steam, which, when added to the reformer at elevated temperatures, provides higher methane conversions. The analysis shown in Figure 2-4 is for LFG.

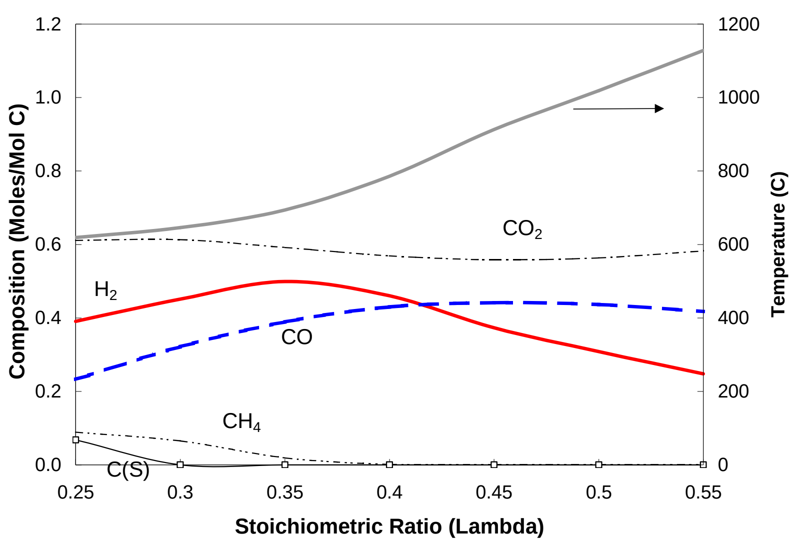

Figure 2-4. The Maximum Conversion of LFG to H_2 + CO Occurs at a Stoichiometric Ratio of 0.38

Catalytic autothermal reforming is a steam-induced microthermal catalyzed reactive process, whereas partial oxidation reforming is a macro-thermal reactive process.

Catalytic autothermal reforming systems have a number of advantages. Use of an appropriate catalyst allows lower-temperature reforming and greater product selectivity. Other benefits include higher system efficiency, lower levels of carbon monoxide produced in the reformer, and a wider variety of construction and fabrication options. The combination of water injection and catalyst selectivity means less coke formation, a significant advantage in hydrocarbon processing.

A potential supplier of a reformer, H_2fuel, LLC, has developed a new class of catalyst materials for the autothermal reforming process. The catalyst consists of a substrate and a promoter, in which it is thought that the substrate participates in the oxidation of the carbon, while the promoter dehydrogenates the hydrocarbon. This catalytic activity has been found in various combinations of materials with certain characteristic properties needed for either the substrate or promoter.

The difficulty of converting hydrocarbons to hydrogen is that the hydrogen and oxygen bond at moderate temperatures. Under thermal equilibrium conditions, the reaction product will therefore be rich in water and poor in hydrogen. Argonne National Laboratory (ANL), H_2fuel's R&D partner, has discovered that to get a hydrogen-rich gas one would have to find a catalyst that can "dehydrogenate" the hydrocarbon molecule and then selectivity oxidize the carbon chain. Thus, the catalyst must be bifunctional.

To dehydrogenate a hydrocarbon molecule, one can use metals that dissolve hydrogen such as platinum, nickel, or any Group VII metal. Nickel is the least preferred because an oxidation product thereof, NiO_4, is poisonous. To selectively oxidize the carbon chain, H_2fuel and ANL have found a source of ionic oxygen proves to be quite effective. Ionic oxygen apparently reacts with the double bonds of a dehydrogenated hydrocarbon to form oxygen-carbon bonds. Sources of ionic oxygen are oxides crystallizing in the fluorite or perovskite structure and include ZrO_2, CeO_2, Bi_2O_3, $BiVO_4$, $LaGaO_3$. By combining such oxides with a hydrogen/air mixture over it, H_2fuel and ANL discovered it is possible to obtain hydrogen-rich gas from aliphatic as well as aromatic hydrocarbons.

If, for example, ceria is the oxide ion conducting material and platinum is the hydrogen dissolving metal, a cermet containing the catalyst can be prepared using a solid-state method. The starting powder is a high surface area (about 32 m2/g) doped ceria (Ce0.8Gd0.2O1.9) and a second phase powder is either a metal like Pt or an oxide like CO_2O_3 which is reduced in-situ in the reactor to cobalt metal with such a catalyst, the exothermic reforming reaction can be conducted in the range of 500°C to about 750°C. This is considerably lower than the 1,000°C temperatures required for steam reformers, allowing the reactor to be smaller, and the product gas to contain higher concentrations of hydrogen and less carbon monoxide.

3.0 Technical Approach

3.1 Technical Approach Based on TIAX's HALO Technology

Because of their low cost and widespread availability, the internal combustion (IC) engine has been the prime mover of choice for landfill gas to electricity projects. Unfortunately, IC engines suffer from high engine-out NOx levels, and impurities in the landfill gas preclude the use of post-combustion catalytic reduction techniques. The only NOx reduction technique currently available for LFG IC engines is lean-burn operation. At present, the lowest emitting LFG fired IC engines operate in lean burn-mode and are equipped with prechambers to initiate combustion; NOx emissions range from 0.4 to 0.6 gm/bhp-hr. A 95 percent reduction in NOx is required to meet the new distributed generation target equivalent to central station power plant emissions.

One NOx reduction technique ideally suited to LFG applications is hydrogen assisted lean operation (HALO). Because hydrogen has wide limits of flammability, it allows combustion at ultra-fuel lean-conditions, drastically reducing NOx emissions. HALO for natural gas-fired engines is a well-documented idea that has been studied by numerous groups, including TIAX over the past 25 years[15,16,17,18]. Modeling and engine testing performed by TIAX for two separate commercial clients has shown that, for natural gas engines, the lean limit can be extended from a relative air/fuel ratio, lambda of 1.6 to a lambda of over 2.5 by replacing a small percentage of the natural gas with hydrogen. For lambda values greater than 2.2, the NOx is virtually zero.

Reformation of LFG to produce hydrogen has also been investigated[19,20]. Most of these studies have focused on the operation of fuel cells with the LFG reformate. For fuel cell applications, significant clean up of the LFG and/or the produced hydrogen is required. Sulfur, siloxane and other contaminants in the LFG adversely affect the performance of low temperature shift catalysts that are needed to achieve a high hydrogen yield. Furthermore, separating hydrogen from the reformer product stream results in a further loss in efficiency. The authors' proposed

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[15] "Stoichiometric Synthesis, Exhaust, and Natural-gas Combustion Engine," U.S. Patent No. 5,947,063, 1999.

[16] Andretta, D., and Dibble, R. W., "An Experimental Study of Air-Reformed Natural Gas in Spark-ignited Engines," SAE Meeting Proceedings, pp. 85-93, 1996.

[17] Watson, H.C., and Milkins, E. E., "Some Problems and Benefits From the Hydrogen Fueled Spark Ignition Engine," SAE Meeting Proceedings, pp. 1170-1177, 1978.

[18] Proprietary R&D by TIAX, LLC, 1998-1999.

[19] Anoka Landfill Gas-Fueled Molten Carbonate Fuel Cell Project, DOE/NETL Project, (FuelCell Energy, Inc.) DE-AC21-95MC31195, 1994.

[20] U.S. EPA in conjunction with International Fuel Cells to study fuel cell operation on landfill gas.

technology overcomes this difficulty because it requires clean up of only a fraction of the LFG and no post processing of the resulting reformate. For the BioHALO concept, both hydrogen and CO produced by the reformer enhance the lean flammability limit of the LFG.

3.2 Technical Approach

The technical approach is outlined in Figure 3-1, with the individual tasks described in detail below. The open boxes represent tasks that were completed as part of this project. The shaded boxes represent tasks that were deferred for programmatic reasons with the consent of the energy commission after extensive discussions. The reasons that certain tasks were deferred (as shown by the shaded boxes in Figure 3-1 below) were as follows: The field installation was deferred because after the project was well underway, Hess Microgen (the gas-engine supplier) withdrew following a business restructuring, and a substitute commercial partner did not step forward to provide needed matching funds. Also, a host landfill gas site was not available to assist with the field installation and to operate the landfill gas engine facility on actual landfill gas as opposed to synthetic simulated gas. Finally funding and schedule was not available to fabricate and test a real reformer, so the testing reported here was performed using bottled gas. This is the California ARB-approved method of certifying LFG engines emissions levels.

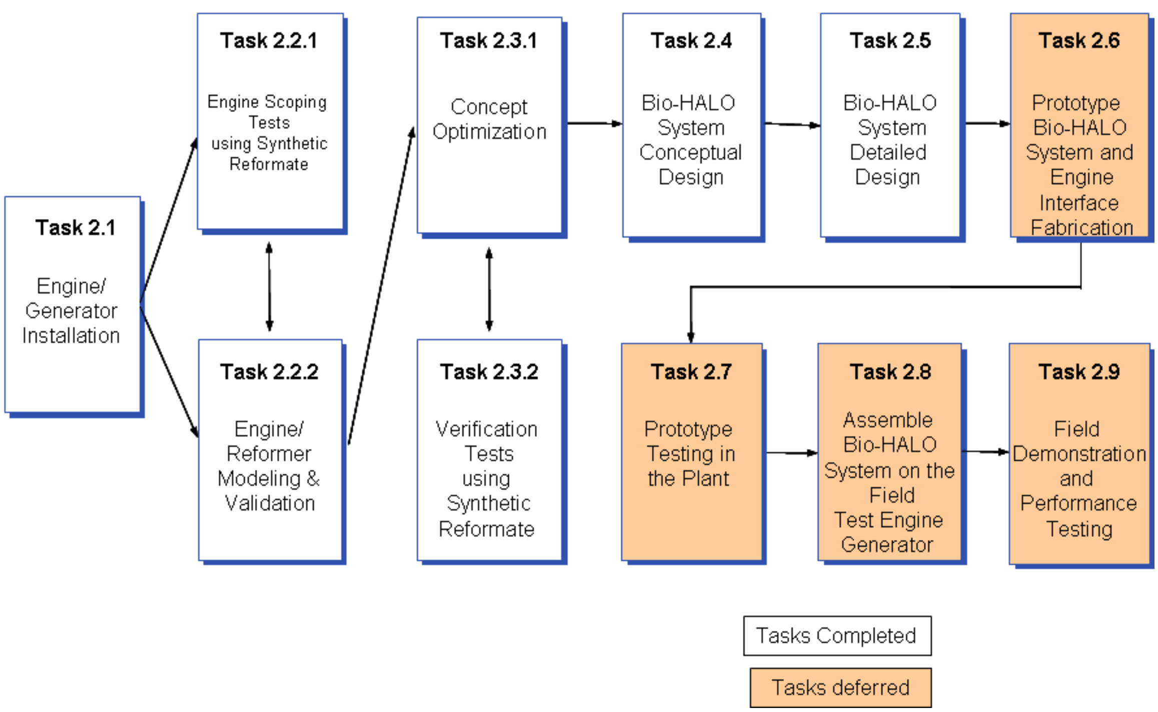

Figure 3-1. Technical Tasks Flow Chart

3.2.1. Task 2.1 — Engine/Generator Installation

As the first task, the 75-kW natural gas engine was modified by the supplier (Hess Microgen) to operate under lean-burn conditions with LFG. Following the modification, the engine was shipped and installed on-site at TIAX. After tie-ins with the LFG fuel supply line, and the electrical load, the generator was operated for no less than six hours to establish benchmark conditions of operation.

3.2.2. Task 2.2 — Engine Scoping Tests and Modeling

Following the installation of the engine, preliminary scoping tests were performed to establish the feasibility of the BioHALO process. The objective of this task was achieved by performing tests on the engine with synthetic-reformate gas. The synthetic reformate was prepared by mixing bottled gas to the desired composition. A limited number of tests was performed to obtain data on engine operation and emissions with LFG alone and combined with the synthetic gas. The aim of this task was three fold. The first was to establish the feasibility of the BioHALO system with an LFG-fired engine. Second, preliminary emission reduction performance and the envelope of engine operating conditions were determined. Finally, based on the preliminary operating and emissions data obtained, strategies for optimal operating conditions for the engine were developed using a computer simulation model of the engine including the on-site fuel reforming reactor. The BioHALO system model was developed using GT-Suite™, the engine simulation package made available through Gamma Technologies with features including:

- Component-based models, allowing for the creation of a library of engine parts that can then be used in various engine configurations.
- Acceptance of user-defined code (i.e., sub-models), that provides maximum flexibility for modeling advanced engine technologies.
- The C-Power interface between GT-Power and Simulink™ for studying engine control strategies.
- Steady-state and transient simulation capability.
- A completely general optimizer, which allows almost unlimited combinations of input and output parameters.

The system model for BioHALO was calibrated and validated with the data acquired in the scoping tests and was extended to predict operating conditions that gave the best NOx emission reductions with acceptable engine operation and fuel economy. Screening of BioHALO concepts benefited from several features of this engine simulation package including: (1) the ability to rapidly screen various engine configurations, (2) Simulink support for exploring control strategies, and (3) capability to simulate both steady-state and transient operation.

Efforts in this task included two subtasks. The preliminary scoping tests with synthetic reformate were performed in Subtask 2.2.1, Scoping Tests using Synthetic Reformate. The engine model development and validation was performed in Subtask 2.2.2, Engine/ Reformer Modeling and Validation.

3.2.3. Task 2.3 — Conceptual Process Optimization

The modeling results in Task 2.2 provided a map of system operating conditions versus the target goal of NOx reduction and engine efficiency. From these results, the authors developed conceptual candidate system arrangements. Each candidate configuration included different sets of system specifications such as:

- Choice of pressurized versus atmospheric reformer.
- Air/fuel ratio of the reformer operation.
- Reformer heat recovery and preheat.
- Water shift/water recovery.
- Turn-down ratios.
- Buffer of hydrogen-rich reformate to support transients.

Next, additional engine tests were performed to screen and analyze the proposed conceptual configurations. Building on the results, recommendations for the reformer-engine arrangements were developed to guide the design of a test plan for verification engine testing. These configuration screenings and evaluations, leading to the recommended configuration, were performed in Subtask 2.3.1, Concept Optimization.

After the recommended optimal process configuration and operating strategy were identified in the concept optimization effort, the next step was to conduct a series of verification experiments on the engine at TIAX with the recommended configurations tested. The test plan for these tests was developed, and the tests performed in Subtask 2.3.2, Verification Tests Using Synthetic Reformate. As the subtask title notes, these recommended concept verification tests were performed using synthetic reformate.

Based on the results of the verification tests, the recommended process configuration and operating strategy were modified. In this sense, Subtasks 2.3.1 and 2.3.2 were iterative in nature.

3.2.4. Task 2.4 — BioHALO System Conceptual Design

This task was the logical next-step to the previous task. In this task, the BioHALO conceptual design was completed. The conceptual design served as the pre-engineering phase and developed overall system process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), control schematics, etc. Key system specifications such as those listed below were established:

LFG-Engine	Autothermal Reformer
Target A/F ratio Reformate/LFG ratio Spark timing Intake pressure Intake temperature Duty cycle	Required flowrates Acceptable reformate temperature range Reformate hydrogen concentration System pressure Duty cycle
Exhaust Oxidation Catalyst (if required)	**Controls**
Exhaust temperature range Exhaust flowrate Exhaust HC and CO concentrations Conversion efficiency required Durability expectations	Type of control algorithm reqired Number of control command outputs and sensor inputs needed Sensor requirements Processor requirements

As part of the conceptual design, the authors also included a preliminary manufacturing cost analysis of the selected configuration.

3.2.5. Task 2.5 — BioHALO System Detailed Design

Following the development of the conceptual design and establishment of system specifications, a detailed engineering design of the BioHALO system was developed. The engineering designs produced in this task were of sufficient detail to enable execution of equipment construction and installation. Key elements of this task included the production of:

- Process layout drawings.
- System integration details.
- Equipment fabrication drawings.
- System mechanical and electrical drawings.
- Civil construction drawings.
- Control logic schematics.

3.2.6. Task 2.6 — Prototype BioHALO Reformer and Engine Interface Fabrication

In this task, the prototype BioHALO auto-thermal reformer was to be manufactured according to specifications at the H_2fuel plant. *Due to unavoidable delays in test engine commissioning and budget constraints, this task was not completed as part of this project.*

3.2.7. Task 2.7 — Prototype Testing in the Plant

Due to unavoidable delays in test engine commissioning and budget constraints, this task was not completed as part of this project.

3.2.8. Task 2.8 — Assemble BioHALO System on the In-Field Test Engine/Generator

Due to unavoidable delays in test engine commissioning and budget constraints, this task was not completed as part of this project.

3.2.9. Task 2.9 — Field Demonstration and Performance Testing

Due to unavoidable delays in test engine commissioning and budget constraints, this task was not completed as part of this project.

3.3 Process Modeling

One of the products of Task 2.2 of the referenced grant agreement is a process modeling report. The original plans for completing the effort contained in the Work Statement for this grant agreement, as documented in the TIAX proposal to the Commission that resulted in the grant agreement, were to install the demonstration engine/ generator procured for the project at the host landfill demonstration site. Once installed at the site, original plans were to complete an initial set of scoping tests to supply data to a planned process modeling and development effort. As originally planned, this initial set of scoping tests would be quite limited in nature, given that they would be performed in a field setting that constrains the number and type of process and emissions measurements that can be taken. The envelope of engine/generator operating conditions that can be tested is similarly constrained in a field setting, as is the length of time over which effective testing can be performed. Given these constraints, the originally planned project was going to rely on process modeling using the GT-Suite™ engine simulation package to define strategies for optimal operating conditions for the engine and hydrogen-producing reformer based on the limited scoping test data obtained in the in-field testing.

As the project proceeded, however, it became clear that installing and operating the demonstration engine/ generator at the landfill host demonstration site would be too time-consuming and costly to support the initial scoping tests. Thus, it was decided instead to install the engine/ generator in the engine testing facilities at the TIAX pilot plant in Cambridge, Massachusetts, and complete the initial tests in this more laboratory-like setting. Having made this decision, it became possible to more completely instrument the test engine/ generator, thereby significantly expanding the number and type of process and emissions measurements that could be made in the initial tests. Moreover, the envelope of operating conditions that could be tested was similarly significantly expanded, and the ability to complete an initial test program over a much expanded time period became possible. With this increased testing flexibility and expanded measurement capability, the need to do process modeling to define optimal operating strategies was eliminated. Instead of having to rely on computer simulation of engine and reformer operation to explore various operating configurations and parameter settings, it was now possible to obtain actual test data to confirm the effects of these configurations and parameter settings on engine operation and emissions. Thus, the test data presented and discussed in the Synthetic Reformate Scoping Test Report, submitted on October 28, 2005, was used in the BioHALO process development effort in lieu of process modeling data that was originally planned.

4.0 Results of Test Engine Installation and Commissioning at TIAX

In the initial tasks of the project, the demonstration engine/ generator was to have been installed at the host site, and an initial set of scoping tests completed to supply data to the process modeling and development effort. The authors had hoped to have scheduled the delivery of the engine/ generator to the host site during May 2003, but continuing delays in obtaining the needed data and interconnection drawings for the engine/ generator system to support the preparation of the applications for permits required for site installation significantly delayed this effort.

Once the engine/ generator had been installed and operational at the site, an initial series of scoping tests were planned as noted above. However, given continuing delays in getting the necessary air district and utility approvals to install and operate a grid connected generator at the site, it became clear that this initial set of tests would not be possible at the site for an extended period. Thus, it was decided to complete the initial tests at the engine testing facilities at the TIAX pilot plant laboratory in Cambridge, Massachusetts. The approved test plan was revised to reflect this change in initial scoping test location, and was approved by the energy commission. A timeline showing the reasons for the delays is provided in Appendix A.

The test engine/ generator was shipped to the TIAX engine laboratories in Cambridge in early October 2003, and installed in one of the TIAX test stands. TIAX staff in Cambridge subsequently completed a number of engine modifications needed to allow the planned scoping tests to take place. All these modifications were completed during August 2004, and the engine was successfully started and run for several hours using bottled natural gas fuel on September 3, 2004.

Connecting the generator to the Cambridge grid required many months due to a series of problems and setbacks. Most of the delays were associated with getting electrical installation specifications for the local grid interconnection from NSTAR, the local electric and gas utility. During April 2005 the local grid connection was complete. Specifically, the last requirement to establish the generator grid connection was to have an NSTAR representative inspect the installation and approve it. This inspection was completed in April 2005, and approval to bring the generator online was granted. Until then, the engine could only be run at idle. With NSTAR's final installation approval, the engine/generator could then be operated powering a grid load.

Additional shakedown problems were discovered and resolved while attempting to operate the engine at full load, as follows:

- Fan selection for engine cooling: Due to the installation of the shaft encoder, a substitute fan used in automotive (not stationary engine) applications was installed on the engine. During initial operation, it was found that this fan provided inadequate cooling. The original Hess

Microgen fan was reinstalled, along with a more slender version of the shaft encoder which fit around the fan.

- Lube oil overheating: The turbocharger that was installed was providing just enough additional heat to the lube oil that standard cooling was not sufficient. An oil/air heat exchanger was installed to solve the lube oil overheating problem.
- The turbocharger outlet was installed incorrectly by an outside vendor. To correct this vendor mistake, the exhaust piping plumbing was modified to allow the wastegate to fully open.
- The exhaust piping was installed (by the outside vendor) very close to the engine coolant lines without adequate shielding, so appropriate shielding was added.
- One of the cylinder's spark drivers was found to be damaged; this was replaced, along with some coils.
- A replacement flue with a higher temperature rating was installed in the side of the engine laboratory building.

With all these problems resolved, continuous operation of the engine/generator at rated power became possible. The completion of Task 2.1 required operating the engine and verifying acceptable operation for at least six hours. Seven hours of successful operation were completed on May 4, 2005, thereby completing Task 2.1 of the project. Figures 4-1 and 4-2 illustrate the engine operating condition data for this initial engine/ generator operating period. These figures indicate that most of the initial operation was conducted at full engine/ generator load, although operation at 25%, 35%, and 20% load was also established. Figures 4-3, 4-4, and 4-5 show various illustrations of the synthetic landfill-gas mixing system. Also shown are the right and left sides of the installed engine/ generator in the TIAX Cambridge engine laboratory.

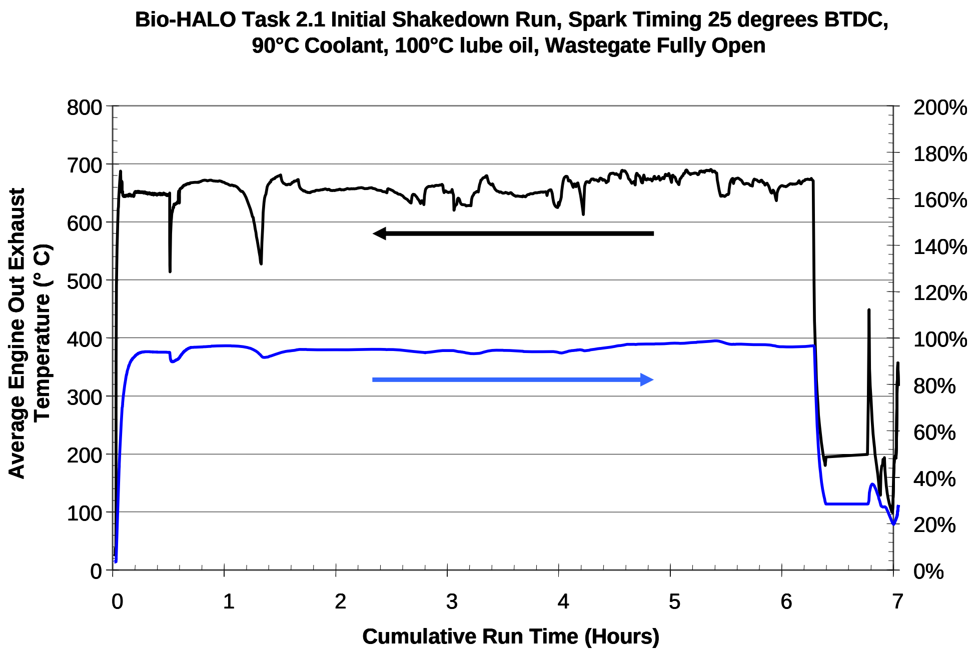

Figure 4-1. Engine exhaust temperature and load for the initial engine/generator operating period

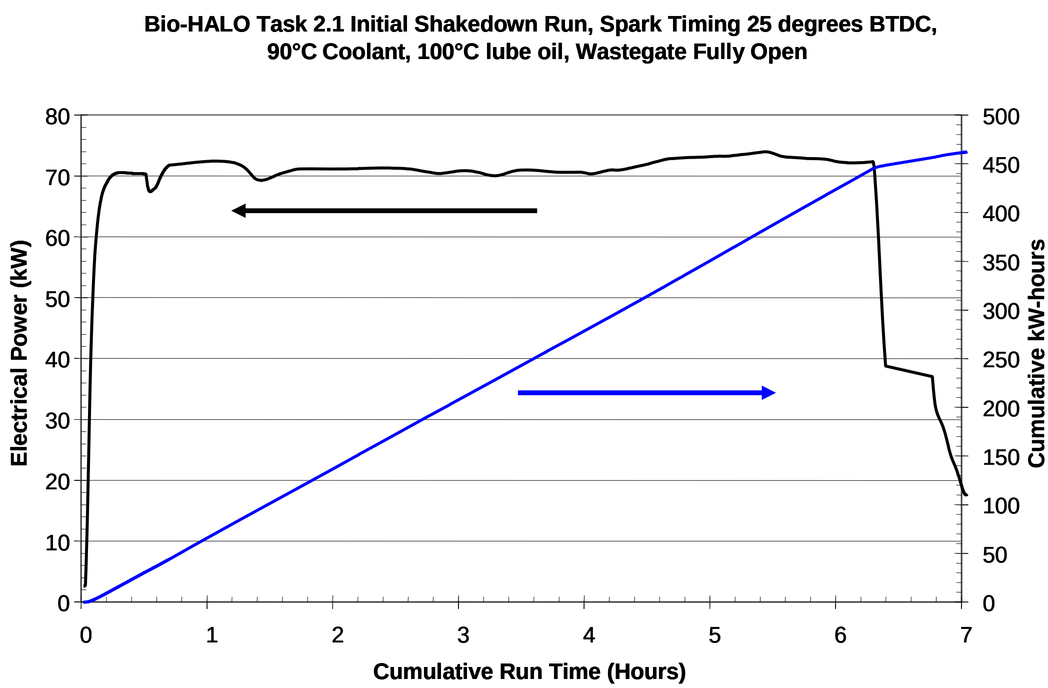

Figure 4-2. Generator electrical power output for the initial engine/generator operating period

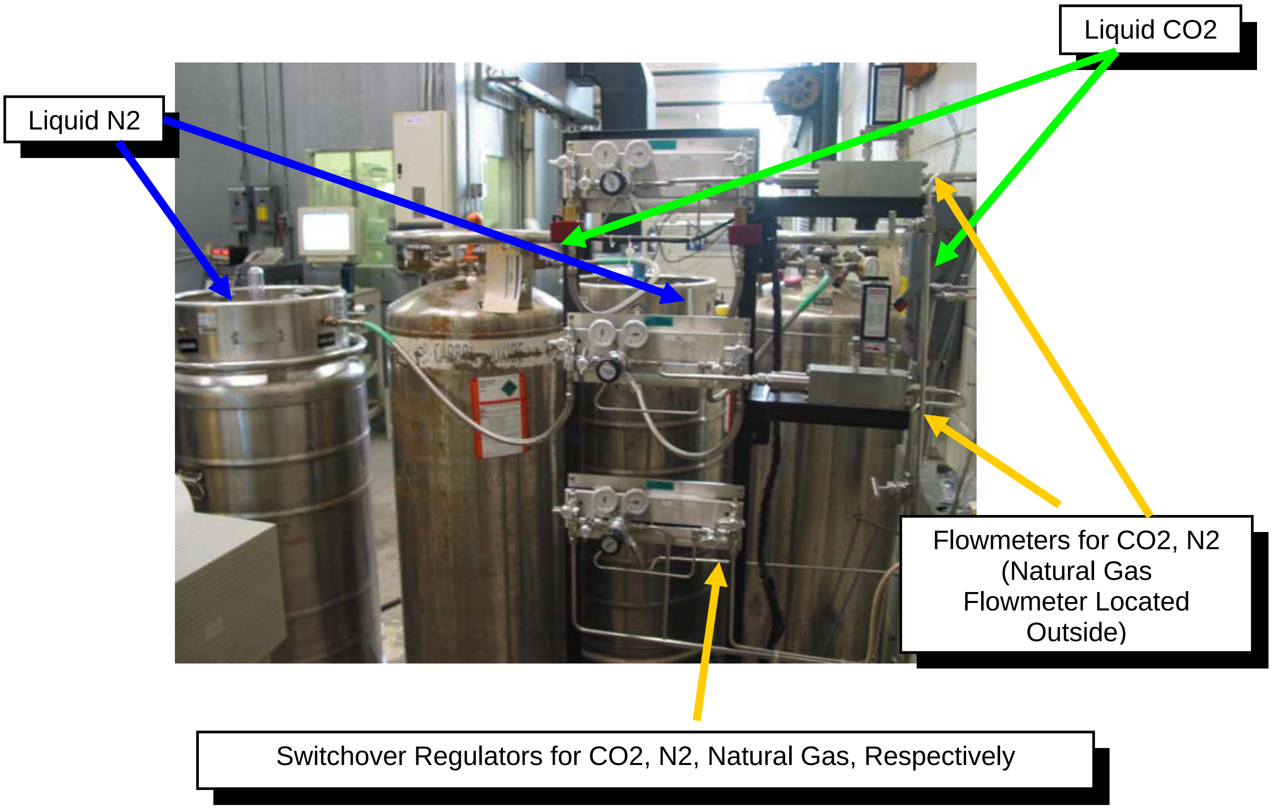

Figure 4-3. View of the synthetic landfill gas mixing system
Photo Credit: TIAX LLC

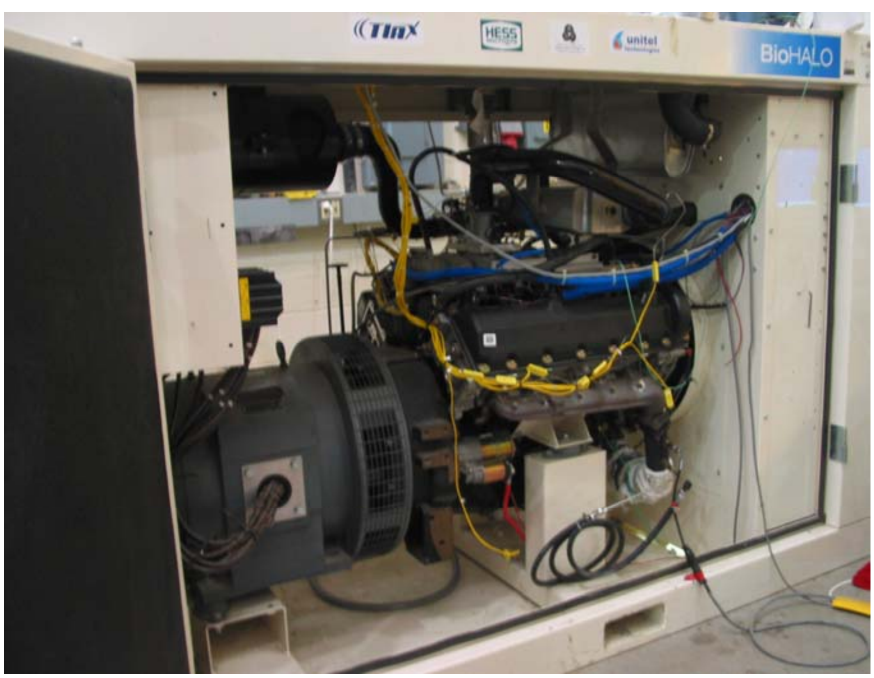

Figure 4-4. View of the right side of the test engine/generator
Photo Credit: TIAX LLC

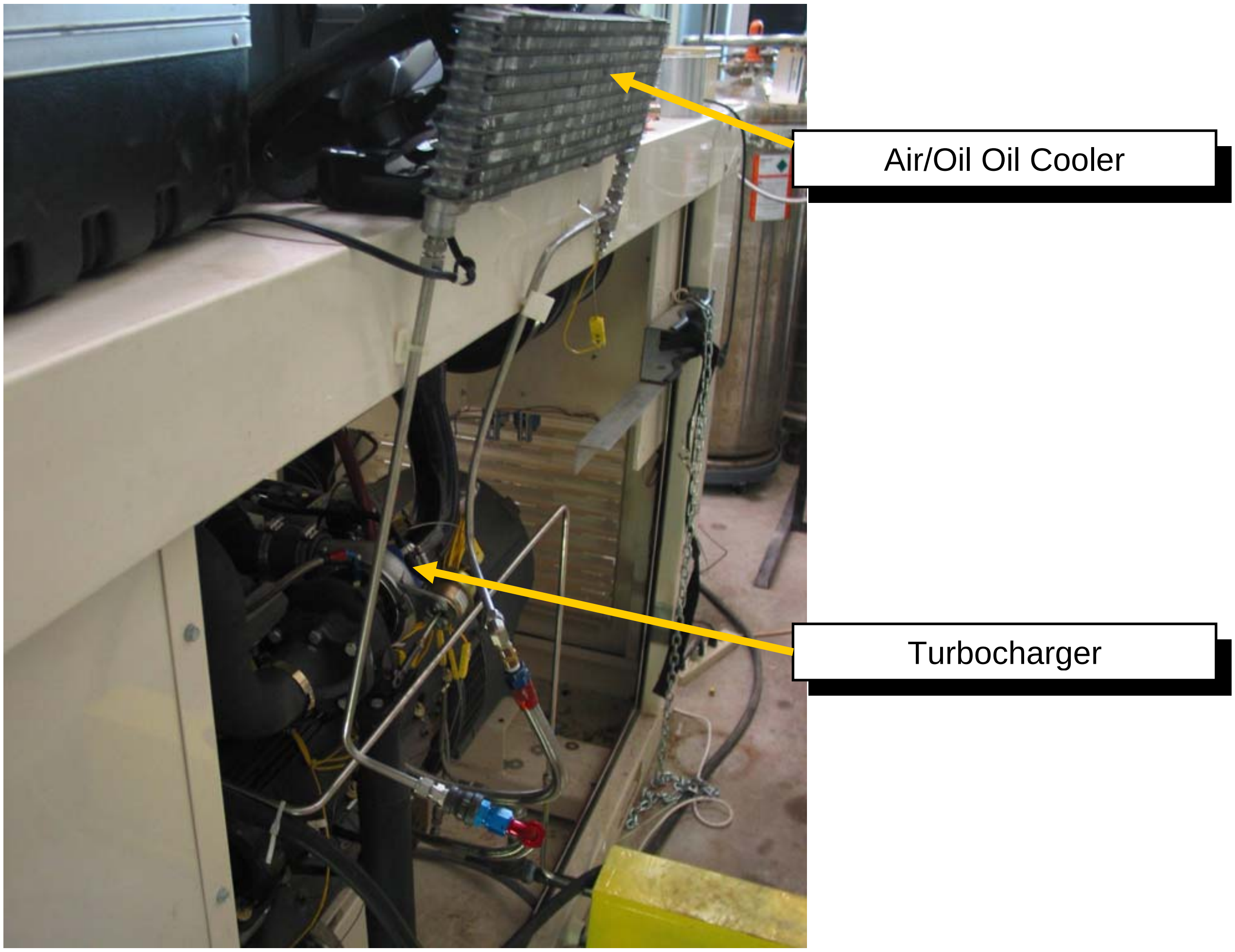

Figure 4-5. View of the left side of the engine/generator showing the oil cooler installed
Photo Credit: TIAX LLC

The authors began preparing a detailed schedule for completing the engine/ generator installation, and completing the initial scoping tests and subsequent verification tests during September 2004.

5.0 Results of BioHALO Scoping Tests (Task 2.2)

5.1 Summary of Scoping Test Results

Task 2.2 of the project consisted of scoping tests using synthetic reformate on an instrumented 75 kW landfill gas engine at the TIAX engine test laboratory. In this initial phase of the development effort, engine operation and emissions performance data needed to be developed with the eventual demonstration engine/ generator fueled with synthetic LFG combined with synthetic reformate having a composition similar to that expected to be produced by the eventual ATR placed at the site. Using a mixture of 57% natural gas, 23% CO_2, and 22% N_2 as the synthetic reformate, the leanest point the baseline engine could be operated was 4.2% O_2 in the exhaust, after which the combustion stability deteriorated. At this point, the engine-out humidity corrected NOx was 440 ppm, which corresponds to 1.8 g/ihp-hr NOx (2.2 g/bhp-hr NOx).

The next set of tests were designed to determine the effect of adding synthetic reformate, which was 52% H_2 and 48% CO. Adding this synthetic reformate mixture allowed the engine to have stable combustion out to ~8% O_2 in the exhaust at a minimum addition rate of 6% H_2/CH_4 (on a LHV basis). Addition of further hydrogen increased the combustion stability marginally, but it still did not allow the engine operating limit to be extended beyond 8% O_2 in the exhaust. At this operating condition, humidity corrected NOx was 20 ppm, which corresponds to 0.12 g/ihp-hr NOx (0.15 g/bhp-hr), a reduction of over 93% compared to the baseline case.

This represented a significant reduction over the best LFG fired lean-burn prechamber engines, whose levels are 0.4 g/bhp-hr, but still did not meet the proposal target of 0.032 g/bhp-hr NOx. Because a 93% reduction in engine-out NOx had been demonstrated and that concurrent TIAX research had shown the ability to go beyond the perceived stability barrier at 8% exhaust O_2, it was recommended that further scoping be completed to reach the 0.032 g/bhp-hr goal. TIAX recommended testing (based upon highest probability of success) of an in-line turbulent mixer first to see of the stability barrier could be broken. If this improved the lean limit, but there was still not enough NOx reduction, EGR, water injection, a high energy ignition system, and finally a combination of all of these were recommended to be attempted. It is believed that a combination of these methods would reduce the NO_x to the desired goal if the turbulent mixer does not extend the lean limit to the desired degree. (Note: These additional tests were successfully carried out in Task 2.3, and the results are provided in Section 6.3 below)

5.2 Scoping Test Program Overview

5.2.1. Rationale for Testing

These initial scoping tests were needed for two reasons. The first was to establish the feasibility of the BioHALO process with an LFG-fueled engine. Second, preliminary emission reduction performance and the envelope of engine operating conditions were determined.

5.2.2. *Test Objectives*

The objective of these initial scoping tests with synthetic reformate was to establish the performance and emissions of the engine over an operational envelope and to establish the operational limits of the engine with and without reformate addition to the LFG fuel. The performance and operational data developed in these tests was to be used as the design basis for the emission reduction technology that was to be demonstrated at the landfill site. Tests were performed to benchmark the engine operating on LFG alone, and then those tests were repeated with synthetic reformate (H_2 and CO) added to the LFG fuel.

5.3 Engine Description

The test engine/ generator was a Hess Microgen generator set comprised of a Ford Power Products Model WSG-1068 V10 engine powering an induction generator with switchgear allowing interconnection to the grid. According to the project plan, it was intended that this engine eventually be installed at a landfill site and grid connected in parallel with the site electrical load. The engine was a 6.8 L natural gas-fueled engine rated at 78 kW (105 hp) at 1,800 rpm using natural gas. It was modified to allow for the full range of scoping testing by the addition of an aftermarket Engine Control Unit (ECU) as well as addition of Ford 1998 MY Crown Victoria CNG fuel injectors. A photograph of the ECU and controls hardware is provided in Figure 5-1. In the figure the ECU is the gold-colored box in the upper right hand corner of the photograph. For these tests, the ECU was connected to a laptop computer, which allowed the on-line adjustment of spark timing, fuel injection timing, and other engine control parameters.

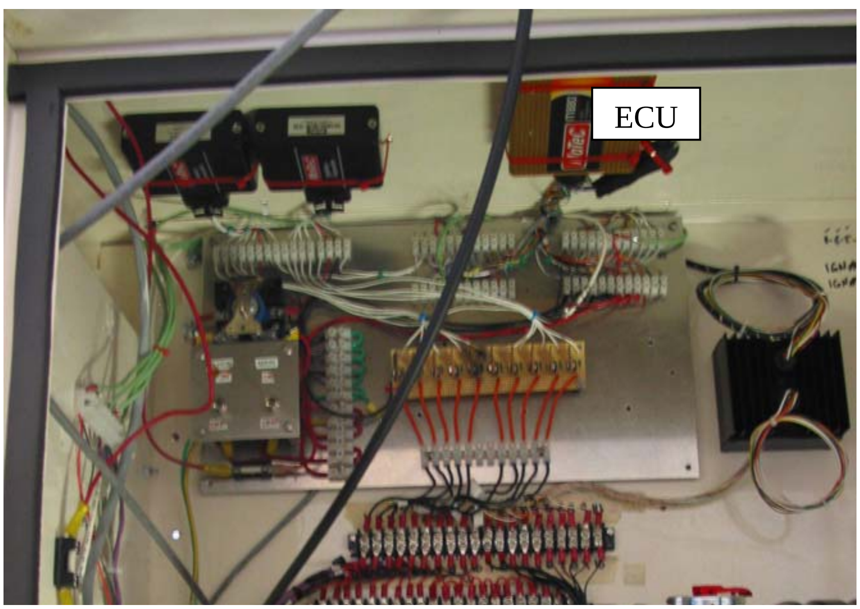

Figure 5-1. Engine Control Hardware
Photo Credit: TIAX LLC

A turbocharger was installed on the engine to allow boosting during the lean operation of the engine to ensure adequate power output. The turbocharger was waste-gated, which allows the boost pressure to be controlled via a valve that allows a controllable quantity of exhaust gases to bypass the turbine. Specifications for the engine are given in Table 5-1.

Table 5-1. Ford Power Products WSG-1068 Specifications

Specification	
Engine type	V10
Bore and Stroke, mm (in)	90.2 x 105.8 (3.55 x 4.17)
Displacement, L (CID)	6.8 (415)
Compression ratio	9:1
Net weight, kg (lb)	290 (640)
Ignition system	Coil on Plug
Rating on NG	78 kW (105 HP) @ 1800 RPM

This specific power engine was chosen from among the Hess Microgen offerings for two main reasons. First, its power output closely matched the desired power output of 70-80 kW for the project (as specified in the TIAX proposal that resulted in this Grant Agreement). Second, this engine was a gasoline engine converted to natural gas operation instead of being a converted diesel engine. Being an original gasoline engine design, the in-cylinder air flow is less turbulent than that for a typical diesel design. This will reduce the tendency for early flame quenching, which can limit the lean ignitability of a lean mixture using a spark ignition system.

A photograph of the engine and generator is shown in Figure 5-2.

Figure 5-2. Side View of Engine/Generator
Photo Credit: TIAX LLC

5.4 Test Plan

5.4.1. Test Procedures

This scoping test program was performed in the TIAX engine laboratory facilities in Cambridge. The engine/ generator, after retrofitting with a turbocharger, was shipped to the TIAX engine laboratory and connected to the local Cambridge grid after installing new protective relaying and obtaining a new cogeneration permit. The engine fuel for all tests was synthetic LFG prepared by mixing nitrogen and carbon dioxide with bottled natural gas fuel to a composition that simulates the diluted fuel present in typical landfill gas. This composition is given in Table 5-2. The heating value of the synthetic LFG blend was 550 BTU/ft3, which is at the high end of the range for LFG fuels. Oxygen, present in landfill gas in very small concentrations, was not used in preparing the synthetic LFG. The N_2 and CO_2 for preparing the synthetic LFG was supplied from liquid N_2 and CO_2 dewars in the engine laboratory. The liquid gases were evaporated, brought to ambient temperature, and metered at appropriate flowrates into the engine to form the synthetic LFG.

A photograph of the LFG mixing system is shown below in Figure 5-3. The mass flow meters are shown in the right of the photograph; these allow measurement of the flow rates of the CO_2 and N_2. The actual flowrates of the gases were controlled via a needle valve before being metered into the engine. The three panels in the middle of the photograph are the regulators and switchover systems for the gases, and the dewars may be seen behind the regulator rack.

Figure 5-3. Synthetic LFG Mixing System with Mass Flow Meters
Photo Credit: TIAX LLC

A schematic of the BioHALO experimental setup is included in Figure 5-4.

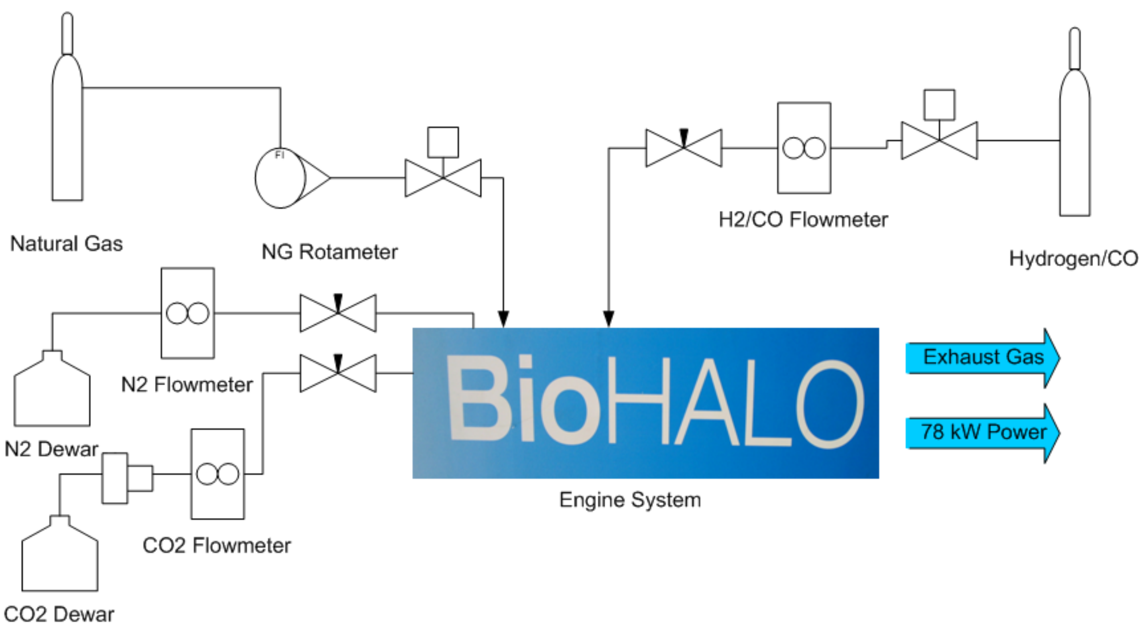

Figure 5-4. BioHALO Schematic.

The goal of the reformate mixing was not to duplicate a specific landfill gas composition, but provide a representative dilute fuel mixture to the engine to adequately determine performance of the BioHALO system.

Table 5-2. Average Synthetic LFG Composition Ranges Over Test Matrix

Component	Concentration, %vol dry
Natural Gas	57 ± 3
CO_2	21 ± 2
N_2	22 ± 2
Heating Value	550 BTU/ft^3

The natural gas used during testing was supplied in 2200 cubic feet six packs of bottled gas. The composition of the natural gas is given in Table 5-3.

Table 5-3. Natural Gas Composition

Component	Concentration	Component	Concentration
Methane	93 %	Ethane	2.4 %
N_2	3 %	Propane	0.5 %
CO	1 %	N-Butane	0.1 %

Table 5-4 provides a summary of the matrix of the scoping test conditions. The following paragraphs provide discussion of this test matrix.

Table 5-4. Test Matrix

Test Set	Description
1	**Baseline Test using LFG.** Engine operating at rated speed of 1,800 rpm with fixed generator load at engine wide open throttle, standard spark timing
2	**Air/fuel Ratio Scoping using LFG.** Engine operating at rated speed of 1,800 rpm. Vary exhaust O_2 from 4% to the lean limit of stable operation in 2% increments. Maintain IMEP at the same level as the baseline test.
3	**Synthetic Reformate Testing using LFG and Reformate.** Engine operating at rated speed of 1,800 RPM. Vary reformate addition rate from 2% of the LHV of the engine fuel to 10% of the LHV in 2% LHV increments. At each addition rate, vary exhaust O_2 from 4% to the lean limit of stable combustion in 2% increments. Maintain IMEP at the same level as the baseline test.

Test Set 1 was carried out to establish the baseline for the engine at the rated standard design operating conditions using LFG. This test data provided insight into the allowable combustion stability criteria for the engine. The baseline operating condition for this particular engine corresponded to air/fuel ratio of 1.15, very close to stoichiometric (15% excess air). Specifically, the objective of the BioHALO process is to maintain or improve the combustion stability of the engine compared to baseline engine operation. This baseline engine operating condition was repeated at the beginning of each test day to ensure the integrity and consistency of the experimental setup, instrumentation, and engine performance.

Test Set 2 defined the lean limit of stable combustion in the standard engine configuration using LFG. In this set, the exhaust O_2 was varied from 4% to the lean stability limit in increments of 2% O_2. The engine indicated mean effective pressure (IMEP) was kept constant (within the accuracy of the experimental configuration) at the level for the baseline test by varying the discharge pressure of the turbocharger. Because combustion phasing affects engine NOx production, fixed combustion phasing, as determined by the location (crank angle) of peak cylinder pressure, was employed to normalize the test data. Exhaust O_2 concentration was used as the test variable to avoid confusion regarding the definition of relative air/fuel ratio when hydrogen is added to the ingested mixture.

Test Set 3 established the extent that the lean limit of combustion can be extended by adding hydrogen rich reformate to the engine's LFG fuel. Reformate addition rate was varied from a value corresponding to a H_2 flow of 2% of the lower heating value (LHV) of the fuel feed to the engine (LFG/ reformate mixture) to 10% of the fuel LHV. At each reformate addition rate, the excess air supplied to the engine was increased incrementally using the turbocharger. Thus engine exhaust O_2 was increased systematically to a point where combustion was no longer stable. Previous modeling showed that adding reformate at 6.75% of the fuel LHV is near the optimum condition for NOx emissions reduction at acceptable engine operation. This condition was bracketed by sweeping from 2% to 10% in logical increments. Similar to Test Set 2, IMEP was kept fixed at the level for the baseline test by varying the discharge pressure of the turbocharger. Also similar to Test Set 2, fixed combustion cylinder peak pressure phasing was employed to normalize the test data.

The composition of the synthetic reformate is given in Table 5-5 and compared to an actual reformer output. This composition is that predicted by Unitel as being the output of its autothermal reformer when fed by LFG with the composition given in Table 5-2. As noted above, the synthetic reformate was prepared to the composition given in Table 5-5 by mixing bottled gases.

Table 5-5. Synthetic Reformate Composition from Reformer

Component	Actual Unitel Reformer Output Concentration, %vol	Reformate Composition Used in the Testing Reported Here, % vol
H_2	14.1	52
CO	13.2	48
CO_2	9.6	Omitted because simple diluents
N_2	46.8	
H_2O	16.3	--

For reference, a photograph of the reformate injection system is shown in Figure 5-5. The air intake is the large black tube that runs diagonally across the photograph. Synthetic reformate was injected into the engine prior to the compressor as shown. For this phase of testing, only pre-turbocharger injection was done.

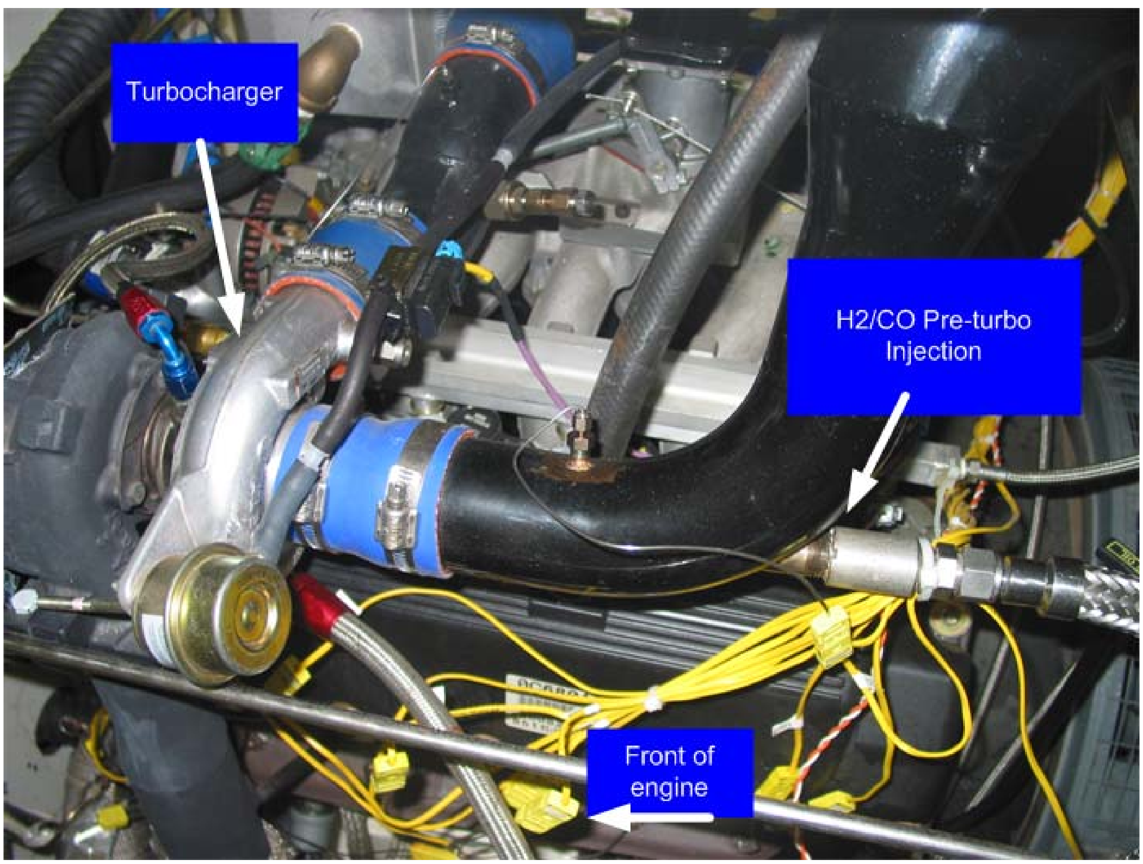

Figure 5-5. Photograph of the Reformate Injection System
Photo Credit: TIAX LLC

The actual reformate mixture injected into the engine was composed only of the fuel components of the reformate, as these are the only components that will extend the stable operating limit of the engine. The CO_2, H_2O, and N_2 normally present in the Unitel reformer output simply dilute the mixture. The resulting in-cylinder mole fractions of CO_2, H_2O and N_2

were not significantly impacted. This was done to maximize testing effectiveness for gas consumption as well as for experimental convenience.

5.4.2. Test Measurements

The engine operating parameters that were measured for each test, along with the instrumentation used to measure these, are listed in Table 5-6. The output from each measurement instrument was recorded in data acquisition computers. The cylinder pressure was recorded with high-speed equipment with 1 degree crank angle resolution, while the other parameters listed in Table 5-5 were recorded at a maximum of 1 Hz, as this was all the resolution that was necessary. "Adapt CAS," a commercially available heat release and engine combustion analysis software, allowed tracking the variation of cylinder pressure with engine crank angle for each cycle and calculating the IMEP for each cycle based on these data. The software also performed statistical analyses to calculate the coefficient of variance (COV) of the IMEP and the lowest normalized value (LNV) of the IMEP over a number of engine cycles. These measures were used to identify when engine combustion began to become unstable as the lean limit of combustion was approached. The software also identified the location (crank angle) of the peak cylinder pressure, the location of the 50% combustion completeness point, and the crank angle range of 10 to 90% combustion completeness. These were also indicators of combustion stability or incipient instability.

Table 5-6. Measured Engine Operating Parameters

Parameter	Measurement Method
Cylinder pressure versus time	Kistler 6117 Spark Plug/Transducer
Engine crank angle versus time	BEI HS35 Shaft encoder
Manifold air pressure (MAP)	Delco boost pressure transducer
Engine speed	BEI HS35 Shaft encoder
Engine power output	Measured using Hess monitoring software
Generator power output	Hess monitoring software
Turbocharger intake temperature	Thermocouple in tap in engine intake
Manifold charge temperature	Thermocouple in tap in intake manifold
Exhaust temperatures	Thermocouples in tap in engine exhaust
LFG fuel flowrate	Omega Industrial Rotameter
Reformate flowrate	Mass flow meter in reformate feed line
Combustion air flowrate	SuperFlow flow turbine in air intake
Exhaust O_2 concentration	Horiba MEXA 7500D

For all tests, engine exhaust concentrations of CO_2, CO, NOx, and total hydrocarbon (THC) were also continuously monitored in addition to the oxygen concentration. The engine test facility at the TIAX Cambridge laboratories is equipped with a Horiba MEXA 7500 dual channel continuous emission monitoring system that was used to continuously monitor engine exhaust.

This system includes a paramagnetic O_2 analyzer, non-dispersive infrared (NDIR) CO and CO_2 monitors, a heated chemiluminescence NOx monitor, and a flame ionization detector (FID) THC monitor. Special care was taken when calibrating the O_2 analyzer. A 16% O_2 concentration was used to calibrate the O_2 analyzer so that the lean operating conditions could be adequately captured.

Mass flowmeters, pressure transducers, and thermocouples were calibrated before installation on the engine and held calibration throughout the project. Before testing began, linearization of the Horiba Continuous Emission Monitors (CEM) was done to ensure measurement accuracy down to the lowest levels of desired measurements. The CEMs were calibrated using zero and span gas at the beginning and end of each test day. Zero and span drift were calculated and compared to reference method specifications.

Ambient temperature, barometric pressure, and relative humidity were recorded hourly during each test day. These measurements were used to correct all affected engine operating parameters including indicated torque, indicated power, IMEP, specific fuel consumption, and fuel conversion efficiency.

5.4.3. Data Analysis Procedures

The TIAX heat release and engine combustion analysis software was used to analyze test data obtained. In addition to the IMEP and combustion completion calculations generated by the Adapt CAS system discussed above, this software allowed calculating, evaluating, and plotting a variety of engine operation and emissions parameters such as relative air/fuel ratio (λ) without hydrogen introduction, specific fuel consumption (g/kWh, dry basis), specific emissions (g/kWh, dry basis), the in-cylinder burn rate, the indicated fuel conversion efficiency, and the volumetric efficiency. Of particular importance for Task 2.3 were the NOx measurements and the instruments were calibrated for ultra-low NOx (0-10 ppm). Because IMEP is a measure of normalized engine torque, the engine power output and fuel conversion efficiency are reported as indicated values (i.e., based on measured in-cylinder pressure, not on engine net brake torque).

5.4.4. Quality Assurance Procedures Followed

During test setup and engine testing, a bound laboratory notebook was kept. In this notebook each test's setup was documented using photographs, technical drawings, and text that describes the setup with sufficient completeness that a given test could be duplicated in the future. During testing, daily entries were made that described each test's objective and each test's observations with time stamps associated with each observation. Any abnormal or unexpected events were also noted, with possible explanations and expected effects on the test data or the achievement of test objectives.

In any experimental program there will always be test-to-test variations in the measurement results obtained from repeated tests at the same test conditions. Naturally, it is preferable to minimize this variability. In well-controlled laboratory engine test facilities, it is usually possible to achieve test-to-test repeatability of key performance parameters to within 1%. Nevertheless, it is important to measure the day-to-day variability in key performance parameters over time and use these measurements as a quality check threshold to verify the integrity and consistency of the engine setup and the testing hardware and instrumentation. To this end, the baseline test (Test 1) was performed at the beginning of each test day, as noted above. The combustion stability for this condition, as determined by COV and the LNV of the IMEP, was compared to that for previous test days. If the difference exceeded the quality check threshold, a cause for the difference was sought and corrective action taken. The initial quality check threshold was 3% difference.

The Cambridge office of TIAX is ISO 9001 certified, and certification of the Cupertino office is underway. The TIAX ISO 9001 laboratory and testing procedures with regard to data acquisition, storage, backup, and evaluation were followed throughout the testing.

5.5 Test Results and Discussion

The test plan for Task 2.2 was successfully followed and completed, and the results are presented below. All data shown is an average over 500 engine cycles (i.e., 500 sequences of intake, compression, combustion, expansion, and exhaust for all 10 cylinders). The baseline test results (Test Set 1) are summarized in Table 5-7 below:

Table 5-7. Baseline Test Results Summary

Parameter	Result
Engine IMEP (bar)	8.3
LFG (% Natural Gas, % N_2, % CO_2) composition	57± 3, 21 ± 1, 22± 2
Location of Peak Pressure (deg ATDC)	20
IMEP COV (%)	1
IMEP LNV (%)	96
Spark Timing (deg BTDC)	25 deg BTDC
Average Exhaust Temperature (°C)	512
Exhaust O_2 Concentration (%)	2.5
Calculated Relative Air/Fuel Ratio (-)	1.14
Engine Out humidity-corrected NOx (ppm)	2722
Engine Out humidity-corrected NOx (g/bhp-hr)	12

Table 5-8 shows the results of the stability scoping without the addition of synthetic reformate (Test Set 2).

Table 5-8. Stability Scoping Testing Summary—No Reformate

Parameter	Test Point 1	Test Point 2	Test Point 3
Engine IMEP (bar)	8.3	7.9	7.9
LFG (% Natural Gas, % N_2, % CO_2) Average Composition	57± 3, 21 ± 1, 22± 2		

Parameter	Test Point 1	Test Point 2	Test Point 3
Location of Peak Pressure (deg BTDC)	20	24	18
IMEP COV (%)	1	5	15
IMEP LNV (%)	96	83	-2
Exhaust O_2 Concentration (%)	2.5	4.2	5.5
Calculated Relative Air/Fuel Ratio*	1.14	1.24	1.31
Engine-out humidity-corrected NOx (ppm)	2722	298	436
Engine out humidity-corrected NOx (g/bhp-hr)	12	1.53	2.2

*see Appendix A, Air/Fuel Ratio Calculations

Combustion stability drops off very quickly as the air/fuel ratio is increased beyond 1.24 (24% excess air). For discriminating between stable and unstable combustion, a threshold of 10% COV and/or 75% LNV is typically used, so Test Point 3 would not be acceptable for power production. The excess air at this point, however, does lower the in-cylinder temperatures and thus the thermal NOx production. The volume concentration of NOx for the final point is higher than Test Point 2 even though the exhaust O_2 concentration is higher because of the poor combustion that occurred during Test Point 3 (evidenced by the high IMEP COV and low IMEP LNV).

5.5.1. LFG/Reformate Test Results

For these scoping tests, manual adjustments were made to regulate engine operation conditions (engine load and boost, fueling rate) as well as synthetic reformate composition. According to the program plan, electronic closed-loop controls of these parameters would be employed later in the demonstration phase of the program. The manual adjustment process involved an iterative process. First, the engine was brought to the lean operating condition near Test Point 3 in Table 5-8 using LFG alone, which caused poor combustion stability and low engine power output. Then, a predetermined fixed concentration (based upon an initial fuel flow measurement) of the simulated reformate composed of hydrogen and carbon monoxide was slowly added to the engine. This addition of the hydrogen caused the engine combustion to stabilize and the engine power output to increase. Following that, the desired IMEP and exhaust O_2 concentration was obtained by adjusting the fuel mixture and wastegate position to control the boost of the turbocharger. The manual adjustment nature of this process accounted for the minor variabilities between test points. IMEP was held close to 8 bar in all tests, with lower IMEPs occurring where there was significant combustion instability.

Figure 5-6 is a plot of all the data taken for the LFG/Reformate scoping tests. As may be seen from the graph, the NOx drops dramatically with the increase in excess air (as expected for the thermal NOx mechanism). The exhaust percentile O_2% is used as the abscissa to avoid any possible confusion of the definition of air/fuel ratio once hydrogen is introduced. The ordinate is shown on a logarithmic scale to because of the large range of values. The lowest values obtained were 4 to 10 ppm humidity corrected NOx, corresponding to 0.03 to 0.06 g/ihp-hr (0.06

to 0.08 g/bhp-hr) NOx emissions. However, combustion stability and power output were not acceptable at these points, as will be shown shortly.

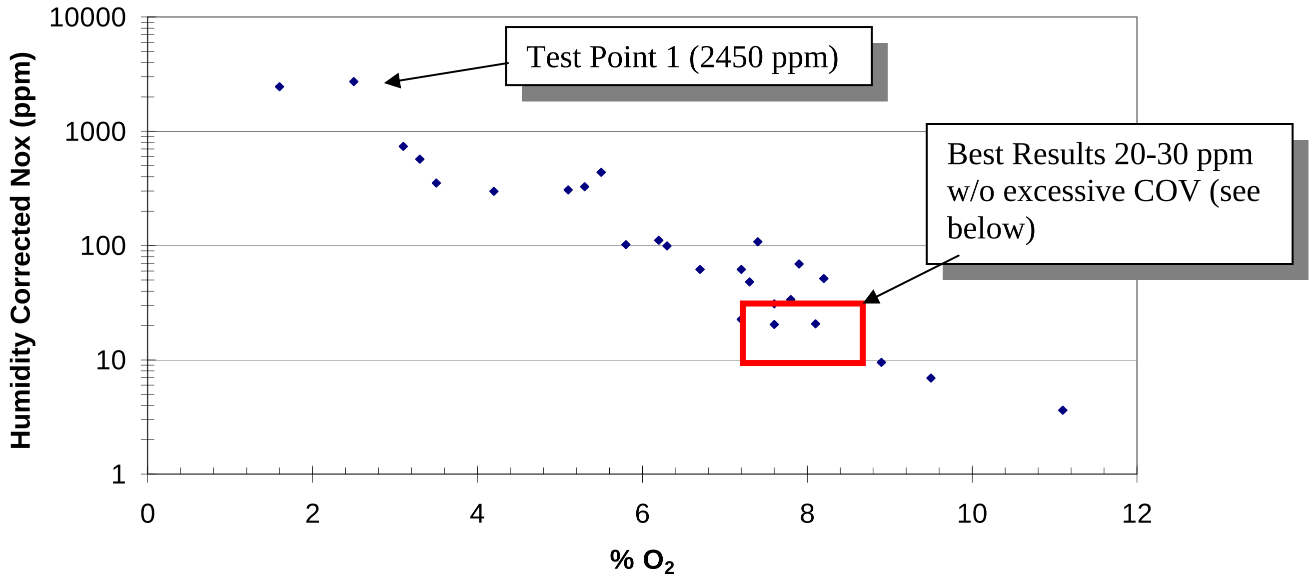

Figure 5-6. NOx Emissions as a Function of O_2 in the Exhaust

Figure 5-6 shows an overall view of the NOx reduction potential of the running the engine at ultra-lean operating conditions. However, more insight may be gained by focusing on the leanest conditions (6% exhaust O_2 or greater) that produce the lowest NOx emissions. This view is shown in Figure 5-7, where values below 160 ppm are shown. Figure 5-9 shows the same NOx results with ppm now in g/bhp-hr. Significant reductions in NOx are shown, with over 99% reduction being accomplished (2450 to below 24 ppm) over the leanest baseline condition. This point is achieved using a reformate addition level of 10% LHV H_2/CH_4. However, even though the NOx at this point is quite low, the combustion stability was not acceptable. This may be seen from Figures 5-8 and 5-9 and the discussion that follows.

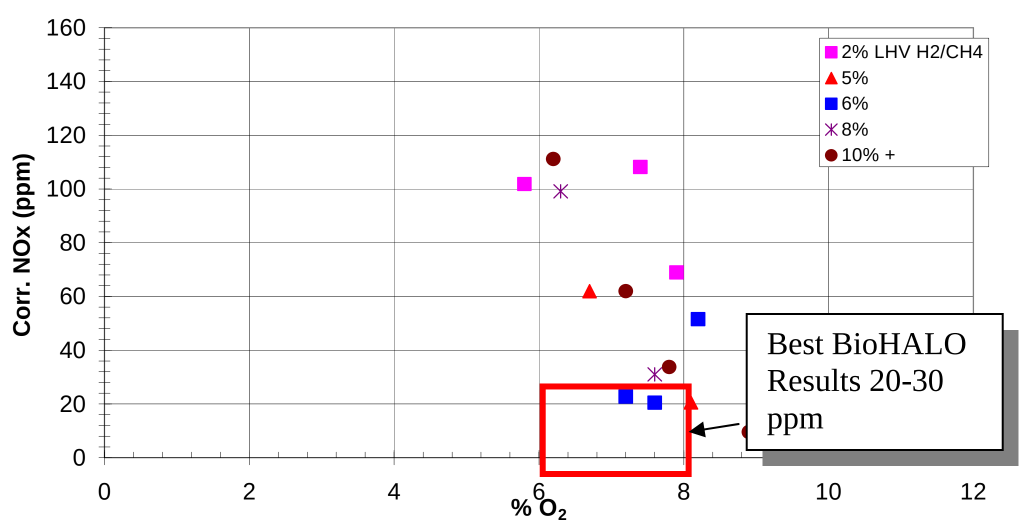

Figure 5-7. NOx as a Function of O_2, with Reformate Levels Identified

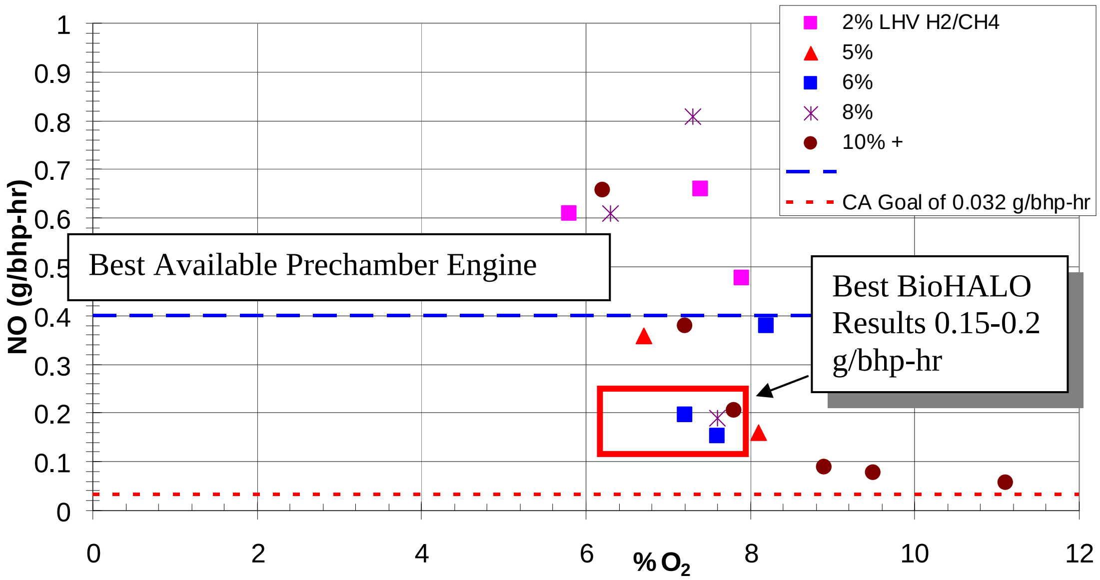

Figure 5-8. NOx as a Function of O_2, with Reformate Levels Identified in g/bhp-hr

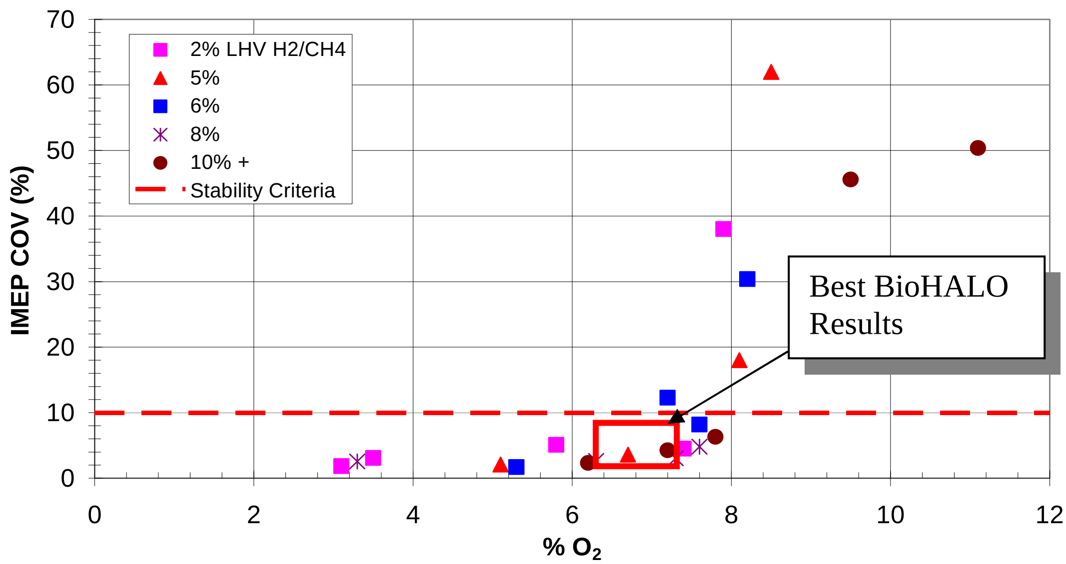

Figure 5-9. IMEP COV as a Function of Exhaust O_2 Concentration

Even with hydrogen addition up to the levels tested here, the lean stability limit is reached at or close to 8% exhaust O_2 (which roughly corresponds to a relative air-to-fuel ratio of 1.6). At even leaner operation ($O_2 > 8\%$), the combustion stability no longer can be held at acceptable levels, even with the addition of additional hydrogen up to the level tested here. This same point may be seen in Figure 5-10, which shows the IMEP LNV.

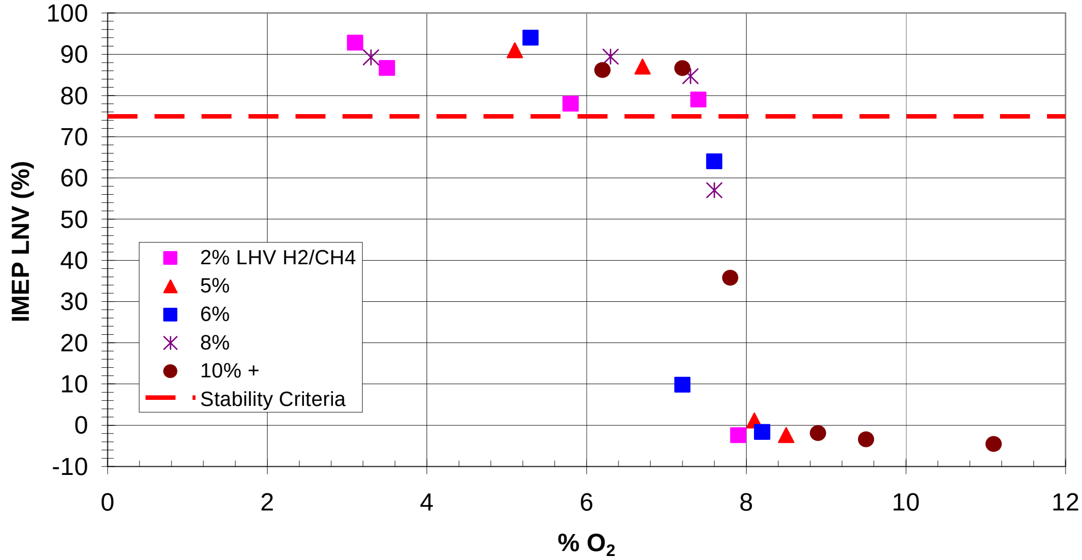

Figure 5-10. IMEP LNV as a Function of Exhaust O_2 Concentration

Applying the filter on the data of a maximum of 10% IMEP COV, the points shown in Figure 5-11 are allowed:

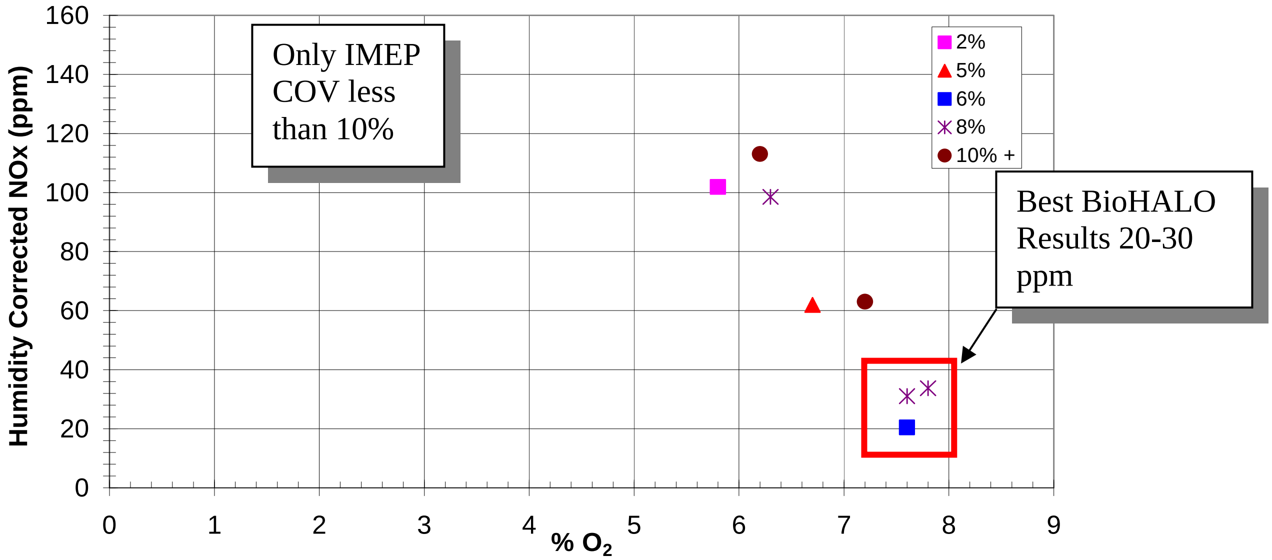

Figure 5-11. NO_x as a Function of Exhaust O_2, Data Points Where IMEP COV Was Less Than 10%

The data in Figures 5-11 and 5-12 indicate that humidity corrected NOx emissions levels of 20 ppm (corresponding to 0.12 g/ihp-hr NOx, or 0.15 g/bhp-hr) can be achieved by adding reformate at a level of 6% or higher and operating the engine ultra lean (7.5% to 8% oxygen in the exhaust). Compared to baseline engine operation, this corresponds to >98% reduction in engine out NOx (see test point 1 in Table 5-8) on a g/bhp-hr basis.

Best bioHALO Results 0.15-0.2 g/bhp-hr

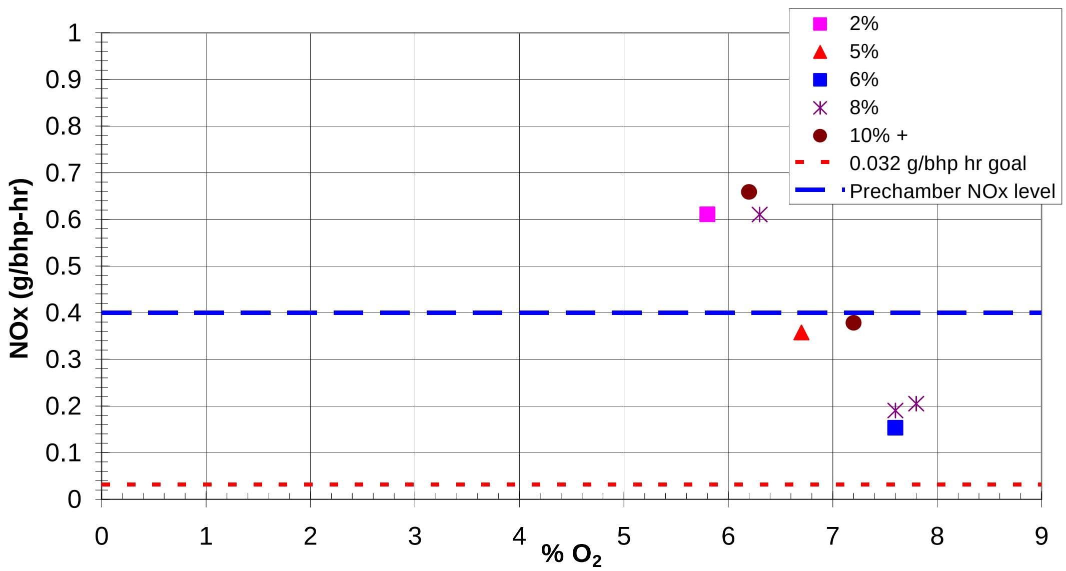

Figure 5-12. NOx as a Function of Exhaust O_2, Data Points Where IMEP COV Was Less Than 10%

5.6 Conclusions and Recommendations From Scoping Tests

This series of scoping tests had shown the ability to achieve a significant 93% reduction in the NO_x emissions levels using reformate, when compared to the NOx at the leanest operating condition without reformate addition. However, the project target of 0.032 g/bhp-hr NOx (sub 10 ppm) was not met, and reaching this target would require an additional 75% NOx reduction. In the tests so far, the lean limit of operation reached was 8% O_2, and the engine would not run at acceptable COV at the lean conditions (beyond 8% O_2 in the exhaust) needed to reach the sub 10 ppm NOx level. Even though the mixture at the best test point was highly dilute due to the presence of N_2 and CO_2 from the synthetic LFG, this dilution is not sufficient to reduce the NOx levels down to the sub-10 ppm level.

In forming a recommendation, the authors noted that achieving an additional 75% NOx reduction is actually not that challenging because of the exponential dependence of NOx formation rate on flame temperature. The rule of thumb is each 20°C drop in flame temperature produces a 50% drop in NOx formation (rate). In other words, engine operation was within feasible striking distance, and all that was needed was a practical means to achieve a flame temperature suppression of about 40°C on average. Four alternatives were examined as explained below, and some of these appeared feasible to pursue and promising.

The first alternative examined was whether cylinder-to-cylinder mixture differences or even unmixed pockets within a cylinder were preventing very lean operation. Such pockets can produce high NOx as is well documented. If this is the case then simply making a homogeneous air-fuel mixture can lower the NOx dramatically. In a separate study on hydrogen supplementation of natural gas engines, TIAX was able (with hydrogen supplementation) to extend the operating limit beyond 8% exhaust O_2. This is shown in Figure 5-13. As may be seen, with 10% hydrogen supplementation, the engine could stably operate at exhaust oxygen concentrations of 9.5%. The constituents entering the cylinder for the results shown in the figure were natural gas, hydrogen, and air.

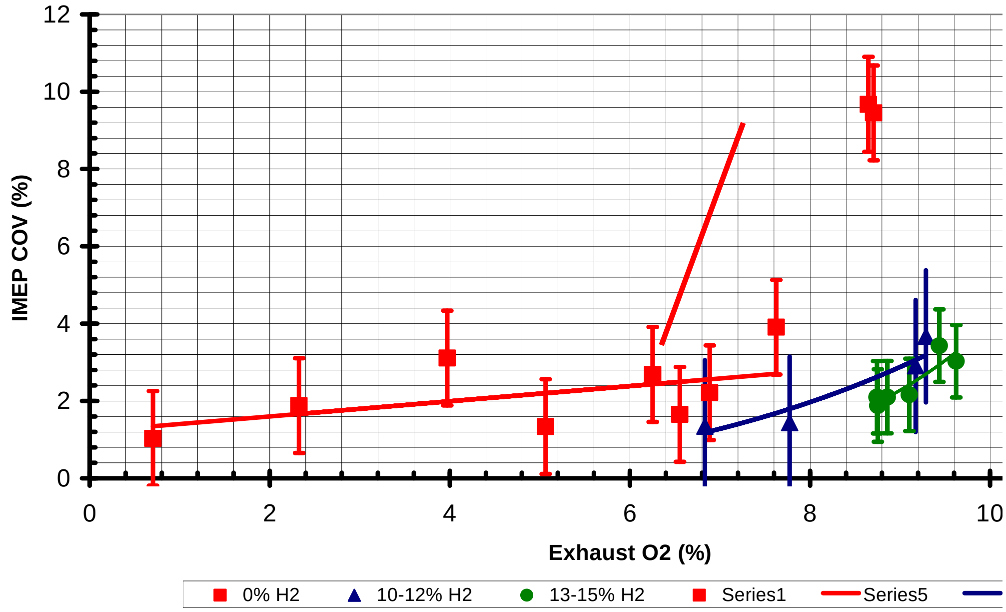

Figure 5-13. Data from TIAX Hydrogen Supplemented NG Engine Work[21]

Comparing Figure 5-13 (HALO) to the comparable shown in Figure 5-9 (BioHALO) suggests that in the BioHALO project, the cylinder constituents of natural gas, hydrogen, carbon monoxide, nitrogen, carbon dioxide, and air ***had not been homogeneously mixed.*** Therefore it was seen to be possible to obtain stable combustion beyond 8% exhaust O_2 with LFG fuel, and thus lower NOx. The logical next step would be to ensure cylinder charge uniformity by using an in-line turbulent mixer.

Additional methods to aid in reducing NOx include:

- ***Further extension of the lean limit with greater hydrogen supplementation***. The addition of more hydrogen could increase the probability of mixture ignitability. Greater than 10% of the fuel LHV would be required. (Of course, here there is a practical constraint with a reformer being able to produce a sufficiently concentrated hydrogen-containing reformate).

- ***Increase in ignition energy supplied***. The tests so far were run with the standard stoichiometric engine ignition system as supplied by Hess Microgen. Lean burn engines typically have higher energy ignition systems than the one supplied with the engine used in this testing. Under hydrogen supplementation at ultra-lean conditions, there is an ignitability limit in the mixture that *a high energy ignition system could possibly overcome, thus reducing NOx.*

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[21] Smutzer, Chad. *Application of Hydrogen Assisted Lean Operation to Natural Gas-Fueled Reciprocating Engines (HALO)* DOE Final Scientific/Technical Report. January 2006.

- ***Swirl/Tumble Modification***. This would affect the behavior of the constituents in the combustion chamber, allowing the fuel and air to mix at the spark plug more easily at leaner conditions and thereby reduce NOx.

- *Exhaust Gas Recirculation (EGR)*. Exhaust Gas Recirculation has the effect of *reducing the peak in-cylinder temperatures and thus reducing NOx* by the addition of the high specific heat components of exhaust gas.

- *Water Spray*. Water sprayed into the cylinder either directly or as another component of the intake air has a similar effect to that of EGR, *reducing flame temperatures and NOx emissions.*

Since a 93% reduction in engine-out NOx had been demonstrated and that concurrent TIAX research has shown the ability to go beyond the perceived stability barrier at 8% exhaust O_2, *it was recommended that further scoping tests be completed to attempt reach the 0.032 g/bhp-hr goal*. TIAX recommended testing various measures in the order of expected probability of impact on NOx, as follows:

First an in-line turbulent mixer would be installed to see if the stability lean limit barrier could be broken. If this improved the lean limit, but there was still not enough reduction, then *EGR, water injection, a high energy ignition system in that order would be tested*. These are all relatively low-cost tests.

Finally testing a combination of all of these was recommended. It was believed that a combination of these methods will reduce the NOx to the desired goal if the turbulent mixer did not extend the lean limit to the desired degree.

6.0 Results of Conceptual BioHALO Process Optimization

6.1 Task 2.3 Summary

Based upon the recommendations from the Task 2.2 test report, a series of tests was conducted in Task 2.3, which was successful in improving the emissions performance of the engine. A modified intake system with improved mixing, improved air delivery, higher hydrogen supplementation, EGR, and water injection were all tried in a series of tests. The best points achieved ranged from 0.035 to 0.047 g/bhp-hr NOx (15% O_2 corrected) with acceptable combustion stability. These points were achieved separately with better mixing, higher hydrogen supplementation, and EGR. However, emissions levels were still slightly above the proposed goals. Following is a list of the conclusions and recommendations from this round of testing:

- The improved mixing provided by the intake redesign proved effective in improving the engine performance.
- The ignition system, when switched to high-energy options, did not show a particular improvement in performance or emissions. Of some concern with the higher energy ignition, is that even though the ignition was achieved of the mixture, the burn times are slightly longer than desirable.
- Water injection was interesting that it allowed for lower NOx emissions when compared to a standard point of similar dilution, but did not improve the emissions to the point beyond emissions targets.
- Because this was a test plan designed to encompass a range of operating conditions, each point was operated for a short duration to finish all of the testing required in the amount of time. To prove the value of the system, it would be desirable to run for a longer period.
- Although targets were not quite met, the results show an impressive emissions reduction from the baseline reciprocating engine technology, resulting in lower *engine-out* emissions than post-aftertreatment for a comparable natural gas-fueled engine.

6.2 Task 2.3 Approach

The best results from Task 2.2 represented a significant reduction over the best LFG fired lean-burn prechamber engines, whose levels are 0.4 g/bhp-hr but still did not meet the proposal target of 0.032 g/bhp-hr NOx. Because a 93% reduction in engine-out NOx had been demonstrated and that concurrent TIAX research has shown the ability to go beyond the perceived stability barrier at 8% exhaust O_2, it was recommended that further scoping tests to be completed in Task 2.3 to reach the 0.032 g/bhp-hr goal. TIAX recommended testing (based upon highest probability of success) of an in-line turbulent mixer first to see of the stability barrier may be broken coupled with increased hydrogen supplementation. If this improved the lean limit, but there was still not enough reduction, EGR, water injection, a high energy ignition system, and finally a combination of all of these were recommended to be attempted. It was believed that a combination of these methods would reduce the NOx to the desired goal if the turbulent mixer did not extend the lean limit to the desired degree.

6.3 Task 2.3 Test Program Overview

6.3.1. Engine Description

As in Task 2.2, the test engine/ generator was the same Hess Microgen generator set is composed of a Ford Power Products Model WSG-1068 V10 engine powering a 78 kW induction generator with switchgear allowing interconnection to the grid. The engine was a 6.8 L natural gas-fueled engine rated at 78 kW (105 hp) at 1,800 rpm. It was modified to fire synthetic landfill gas fuel and retrofitted with a turbocharger and intercooler. Specifications for the engine are given in Table 6-1.

Table 6-1. Ford Power Products WSG-1068 Specifications

Specification	
Engine type	V10
Bore and Stroke, mm (in)	90.2 x 105.8 (3.55 x 4.17)
Displacement, L (CID)	6.8 (415)
Compression ratio	9:1
Net weight, kg (lb)	290 (640)
Ignition system	Coil on Plug

This engine was chosen from among the Hess Microgen offerings for two main reasons. First, its power output closely matches the desired power output for the project as specified in the TIAX proposal that resulted in this grant agreement. Second, this engine is a gasoline engine converted to natural gas operation instead of being a converted diesel engine. Being an original gasoline engine design, the in-cylinder air flow will be less turbulent than that for a typical diesel design. This will reduce the likelihood of early flame quenching, which can limit the lean ignitability capability of a spark ignition system.

6.3.2. Task 2.3 Test Objectives

The objective of these Task 2.3 Process Optimization tests with synthetic reformate was to establish the optimum NOx emissions of the engine over an operational envelope, and to establish the operational limits of the engine with and without reformate addition to the LFG fuel. This set of tests had the objective of decreasing the NOx emissions further to meet BACT goals.

6.4 Task 2.3 Test Plan Description

6.4.1. Test Procedures

This test program for process optimization was performed in the engine laboratory facilities of TIAX in Cambridge. The engine/ generator, after retrofitting with a turbocharger, was located at the TIAX engine laboratory and connected to the local Cambridge grid under the existing TIAX cogeneration permit. The engine fuel for all tests was synthetic LFG prepared by mixing nitrogen and carbon dioxide with the natural gas fuel available. This composition is given in Table 6-2. Oxygen, present in some landfills at only 0.5% concentration, was not considered in preparing the synthetic LFG. The N_2 and CO_2 for preparing the synthetic LFG were supplied from liquid N_2 and CO_2 dewars in the engine laboratory. The liquid gases were evaporated, brought to ambient temperature, and metered at appropriate flowrates into the natural gas fuel supply to form the synthetic LFG.

Table 6-2. Average Synthetic LFG Composition Ranges Over Test Matrix

Component	Concentration, %vol dry
Natural Gas	57 ± 3
CO_2	21 ± 2
N_2	22 ± 2
Heating Value	550 BTU/ft^3

Table 6-3 provides a summary of the matrix of the performed process optimization tests. The following paragraphs discuss this test matrix.

Table 6-3. Test Matrix

Test Set	Description
1	**Higher Hydrogen Supplementation/Improved Setup.** Additional hydrogen supplementation (than prior testing) to be supplied to determine if leaner operation could be achieved. During this task, the intake and boost system were improved.
2	**Baseline with Higher Ignition Energy.** Engine operating at rated speed of 1,800 rpm. Vary exhaust O_2 from 4% to the lean limit of stable operation in 2% increments. Maintain IMEP at the same level as the baseline test. Determine lean limit as compared to prior testing.
3	**Synthetic Reformate Testing with Higher ignition energy.** Engine operating at rated speed of 1,800 rpm. Vary reformate addition rate from 2% of the LHV of the engine fuel to 10% of the LHV in 2% LHV increments. At each addition rate, vary exhaust O_2 from 4% to the lean limit of stable combustion in 2% increments. Maintain IMEP at the same level as the baseline test.
4	**Synthetic Reformate Testing with EGR/Mixing System.** Engine operating at rated speed of 1,800 rpm. At fixed reformate addition rate, vary EGR rate at fixed exhaust oxygen concentration until lean stability limit. An static mixer may also be inserted to ensure a homogeneous mixture of fuel, air, and diluents entering the cylinder.

Test Set	Description
5	**Synthetic Reformate Testing with Water Injection.** Engine operating at rated speed of 1,800 rpm. At fixed reformate addition rate, vary water injection rate at fixed exhaust oxygen concentration until lean stability limit.

Test Set 1, which was higher hydrogen supplementation and an improved intake setup from prior testing, was based on conversations with reformer suppliers that show that the reformer set up could supply a higher amount of hydrogen. Also, the intake was designed for improved mixing. This additional hydrogen had the benefit of allowing leaner operation, which allows more dilutes operation. Additionally in the following test sets, hydrogen supplementation was higher than that of the prior tests in Task 2.2.

Test Set 2 defined the lean limit of stable combustion in the standard engine configuration with higher ignition energy. This test allowed comparison of the BioHALO system with the higher ignition energy system, as well as determine the optimum spark profile (as this is a parameter that may be changed with the ignition system). In this set, the exhaust O_2 was varied from 4% to the lean stability limit in increments. The engine indicated mean effective pressure (IMEP) was improved to close to the level for the baseline test by increasing the discharge pressure of the turbocharger. Exhaust O_2 concentration was used as the test variable to avoid confusion regarding the definition of relative air/fuel ratio.

Test Set 3 established the extent that the lean limit of combustion can be extended by adding hydrogen-rich reformate to the engine's LFG fuel with higher ignition energy. Based upon Test Set 2, the authors selected the optimum ignition profile (the ignition profile was found to not affect COV, so the manufacturer baseline profile was used). Reformate addition rate was varied from 8% to 16%. Similar to Test Set 2, IMEP will be improved to offset the high dilution by varying the discharge pressure of the turbocharger.

Test Set 4 explored the addition of adding EGR/mixing to the intake system to further reduce the NOx emissions. EGR had the potential benefit over pure air dilution of containing water vapor as well as CO_2, which has a higher heat capacity than air. A mixing system downstream of the EGR introduction point ensured that the charge was well-mixed going into the engine cylinder. Tests were run at a range of EGR rates, from 5 to 30%.

Test Set 5 (water injection) was carried out because the prior tests did not show the desired NOx reduction. Water injection is a method that lowers the in-cylinder temperatures during combustion, reducing the NOx output from the engine. Testing was done to explore the amount of water that can be feasibly added to aid in NOx reduction. The composition of the reformate from a typical autothermal reformer is given in Table 6-4.

Table 6-4. Synthetic Reformate Composition From Reformer

Component	Representative Reformer Output Concentration, % vol
H_2	14.1
CO	13.2
CO_2	9.6
N_2	46.8
H_2O	16.3

The primary component of the reformate that will affect the in-cylinder combustion is the hydrogen (due to its high flame speed and easy ignitability), so hydrogen alone was added to the simulated landfill gas mixture. Diluents and CO would also be part of the reformate mixture if an actual reformer were used (the impact on gas mixture composition in the cylinder was not significant).

6.4.2. Test Measurements

The engine operating parameters that were measured for each test, along with the instrumentation used to measure these, are described in Section 5.4.2 above. For EGR, a three-way valve was used to sample inlet air to measure CO_2 intake.

6.4.3. Data Analysis Procedures

The data analysis procedures for Task 2.3 were the same as for Task 2.2 and are described in Section 5.4.3 above.

6.4.4. Data Analysis Procedures

The quality assurance procedures for Task 2.3 were the same as for Task 2.2 and are described in Section 5.4.4 above.

6.5 Test Results of Task 2.3

During testing, TIAX tried a series of configurations to meet the program goals as well as explore a variety of options for each of the proposed methods of NOx reduction. Also, as expected with any experimental program, there were difficulties with the experimental setup that had to be overcome to proceed with testing. A timeline of the testing that this report covers is shown below in Figure 6-2. Prior to the dates shown on the timeline TIAX was re-commissioning the BioHALO system, as it had been idle for a period of time.

During testing, there were two failures: the VimX ignition system and an intercooler failure. In the initial VimX system received from the manufacturer, the MOTEC system would supply a signal to the VimX ignition system but did so after the signal went through high-voltage igniters. The VimX modules would occasionally misinterpret this high-voltage signal, resulting in a false signal sent to the ignition coil on the engine. Because of this problem, repeatable testing could not be done. To allow for continued testing, TIAX switched back to the Motec ignition system and begin a dialogue with the manufacturer. In speaking to the manufacturer, it was determined that the best way to use the modules was to bypass the high voltage ignitors.

This required a change in the modules, and TIAX performed that change and reinstalled the system. The other hardware failure that was encountered during testing was the Spearco intercooler developed the leak, allowing water to leak into the air stream. Thus, the intercooler was removed and replaced by the "block intercooler."

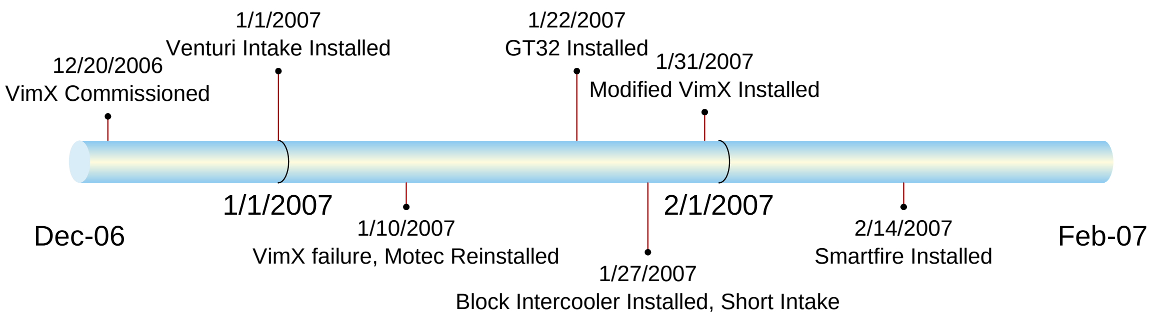


Figure 6-1. Timeline Covered by Report

TIAX systematically changed components so as to improve system performance as well as address failures. The setups for the testing are identified below in Table 6-6. Photographs of the various components will be shown in the results section for each aspect of the test plan.

Table 6-5. Summary of BioHALO Setups for Task 2.3

Setup Variables	Setup A	Setup B	Setup C	Setup D	Setup E	Setup F
Ignition System	VimX	MOTEC	MOTEC	MOTEC	VimX	Smartfire
Turbocharger	GT20	GT20	GT32	GT32	GT32	GT32
EGR System/Intake	Venturi with long intake	Venturi with long intake	Venturi with long intake	Shorter intake/ EGR pre-compressor	Shorter intake/ EGR pre-compressor	Shorter intake/ EGR pre-compressor
Intercooler	Spearco	Spearco	Spearco	Block	Block	Block

The Task 2.3 testing was divided into four areas (based upon recommendations from the Task 2.2 Report) that were explored to determine the effect on the combustion and emissions of the engine: additional hydrogen supplementation, higher ignition energy, higher dilution in the form of EGR and better mixing, and water injection.

The object of these tests was to sweep over a wide variety of points to determine the optimum point, so each test point was relatively short to allow for all of the tests to be accomplished. A typical test day would proceed with the following procedure:

- The engine would be started and idled until the coolant temperature reached approximately 50°C.
- The generator would then be connected up to the electrical grid, bringing the engine speed to 1800 rpm.
- The throttle would be opened, and fuel would automatically be added by the Motec system until a point of about 40 kW was reached. The engine would be kept at this point until the oil and coolant temperatures reached the appropriate operating levels. During this time, the carbon dioxide and nitrogen would be added to simulate the landfill gas.
- At this point, hydrogen would be added to the appropriate level, boost adjusted accordingly, and the desired operating point would be set.
- Once the point reached steady-state, as evidenced by the emissions and the combustion stability, data would be taken for 60 seconds. This time period was chosen to correlate with the fairly standard practice[22] of using 500 cycles of engine combustion data to determine combustion stability, and thus the emissions data would line up with the combustion stability data.

Since there were three systems taking data, (emissions data, the combustion data, and the temperatures and flow rates), the engine would be at each point for a range of 5 to 15 minutes. Some test points would be much shorter because changes between each test point were relatively minor, such as increasing hydrogen flow rate, as stabilization would quickly occur, while at some test points the engine would run for an extended length of time.

6.5.1. Results of Higher Hydrogen Supplementation/Improved Engine Setup

The early stages of this task involved improving the intake system to allow for better mixing, allowing for EGR introduction, in addition to examining the effects of increasing the amount of hydrogen provided to the engine. This setup is shown in the photograph below. In this photograph, the EGR system is not complete yet, but the intake system can be seen. The length of the intake system does lead to a pressure drop, lowering the available boost, but due to the engine geometry this was the only feasible way to include the mixer and the Venturi. Also as mentioned in the timeline, a different turbocharger was installed to improve the airflow rate into the engine. The first turbocharger was a Garret GT -- 20 and had a maximum flow rate of about 120 g per second of air. The second turbocharger tried was a Garret GT -- 32, into this allowed flow rates up to 160 g per second of air. This increase in the airflow rate improved the power density of the engine.

[22] Heywood, John B. *Internal Combustion Engine Fundamentals*. McGraw-Hill, New York, 1988. p 418

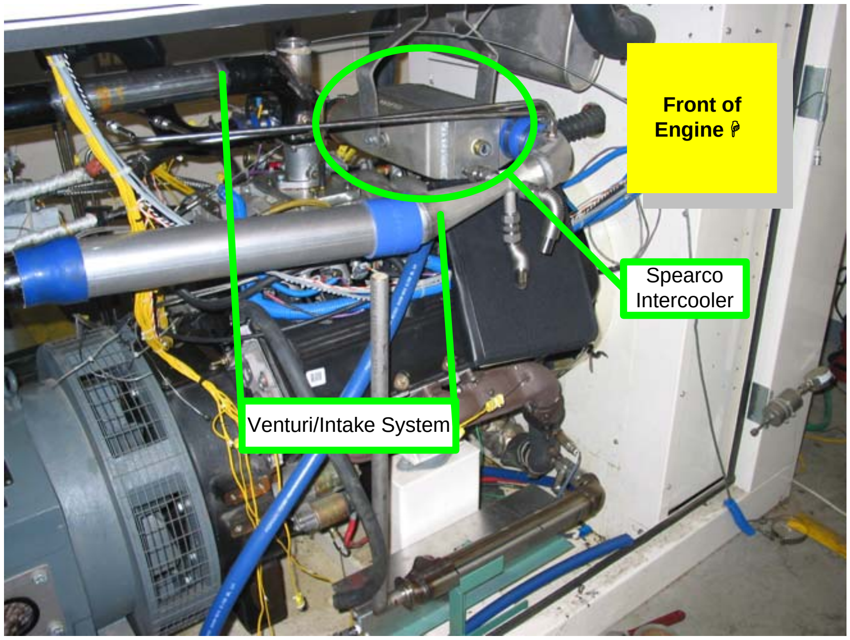


Figure 6-2. Photograph of Intake System
Photo Credit: TIAX LLC

As detailed in the earlier timeline, improvements were made to the intake system to allow for better mixing. The improved mixing allowed a more homogeneous mixture to enter the cylinder, promoting improved combustion. This is evidenced by examining the data and comparing it to the prior runs. As may be seen in Figure 6-3, there is a shift of the lean limit.

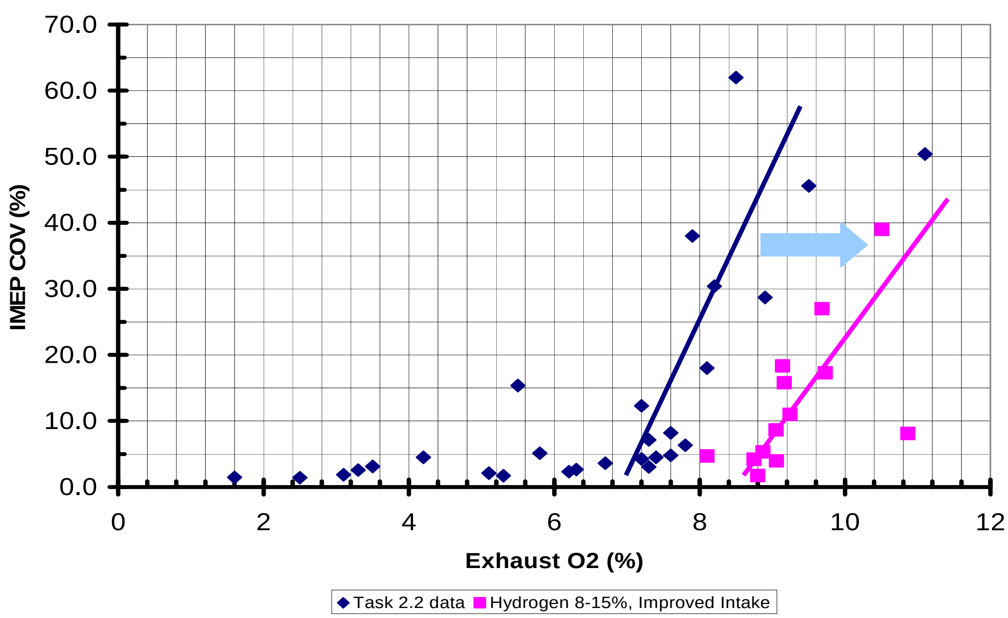


Figure 6-3. Comparison of Task 2.2 data to improved setup and higher hydrogen supplementation

This shift in the allowable operating condition had an effect on the measured NOx. The greater dilution provided by the excess air lowered the peak in-cylinder flame temperatures, reducing the thermal NOx formation. This may be seen in the results, as shown in Figure 6-4.

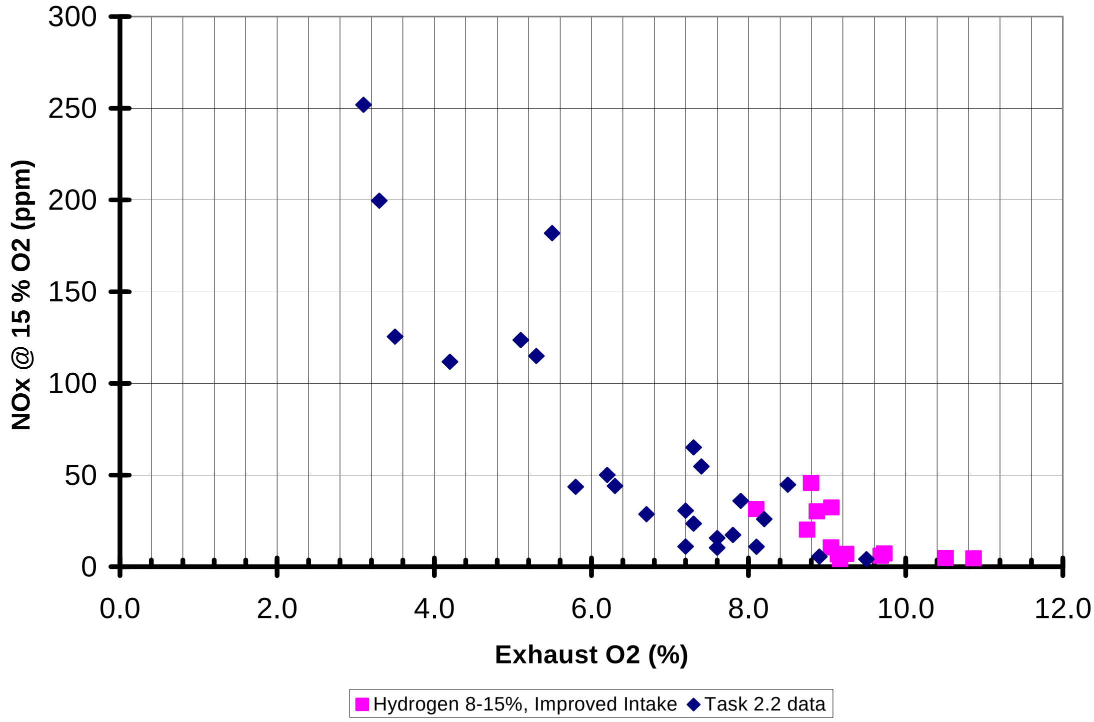


Figure 6-4. Comparison of NOx values for the additional hydrogen supplementation/improved intake

A summary of the points where combustion stability was excellent is shown below in Table 6-6. As may be seen on the amount of hydrogen added, it appears that the main benefit comes from the better mixing of the intake system, although the two best points did have hydrogen supplementation in excess of 10%.

Table 6-6. Summary of points where IMEP COV < 11%

IMEP (bar)	IMEP COV (%)	NOx (Corrected to 15 % O_2) [ppm]	NOx (g/bhp hr, 15% O_2)	NOx (lb/MW hr)	H_2 LHV/CH_4 LHV
5.4	8.1	5	0.035	0.10	13.5%
7.1	4.7	31	0.190	0.56	9.5%
7.5	1.7	46	0.247	0.73	9.5%
6.9	11.0	7	0.044	0.13	11.4%
6.9	4.2	20	0.123	0.36	9.1%
6.8	4.0	32	0.186	0.55	9.0%
7.1	5.3	30	0.166	0.49	8.9%
6.6	8.7	10	0.071	0.21	7.5%

6.5.2. Higher Ignition Energy Test Results

This next section summarizes the results from the higher energy ignition scoping tests. Two commercially available separate ignition systems were tried: 1. Woodward Smartfire Ignition System, and 2. VimX Ignition system. The specifications for the Smartfire system are shown in Table 6-7. Typical stock coils provide 90-120 mJ to the spark plug.

Table 6-7. Smartfire Ignition System Specifications

	Specification
Ignition Type	Capacitive Discharge
Cylinder capability	1-12
Software Control	Windows-based Winfire
Combustion Feedback	Ion current sensing
Coil Type	Custom pencil coils
Spark Plug	Standard J-type
Estimated Spark Energy delivered to plug	151 mJ

The Smartfire system works by discharging a 600 volt capacitor into a coil, which steps up the voltage up to several thousand volts within one microsecond. This large voltage jumps the gap and ignites the combustible mixture in the cylinder. The spark reaches 1 amp and then decays for the order of 40 microseconds. The Smartfire system also has the ability to detect combustion, as highlighted in Table 6-7. Combustion feedback is achieved using ion-current feedback. After the initial spark, a second capacitor is charged, which applies a constant voltage to the plug gap. Combustion, which is occurring as this constant voltage is applied, produces ions. These ions induce a trickle current, which is measured and processed. If combustion does not occur, then there will be no ion current produced, and this will be detected by the Winfire software.

A photograph of the installed Smartfire system is shown in Figure 6-5.

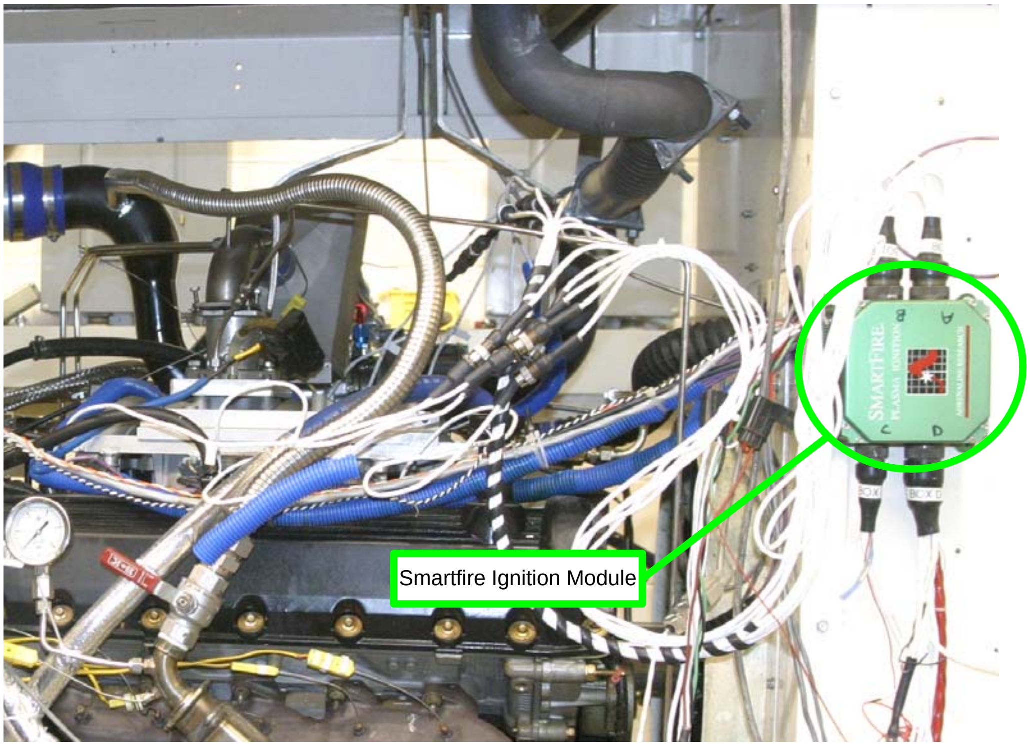


Figure 6-5. Smartfire system installed on BioHALO engine
Photo Credit: TIAX LLC

A schematic of the Smartfire ignition system is shown in Figure 6-6.

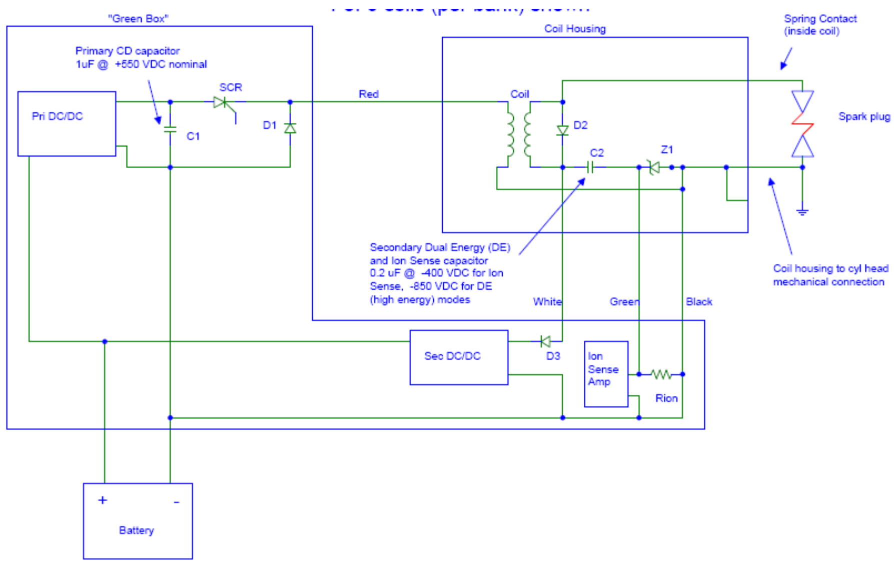


Figure 6-6. Smartfire schematic

The other alternative ignition system also tried during the set of experiments was the VimX system. The specifications of this high energy system are shown in Table 6-8.

Table 6-8. VimX Ignition System Specifications

	Specification
Ignition Type	Capacitive Discharge
Cylinder capability	1-12
Software Control	Windows-based Monitoring
Combustion Feedback	None
Spark Plug	Standard J-type
Coil Type	Standard Coil-over-plug
Claimed Spark Energy delivered to plug	500 mJ

A photograph of the VimX system is shown below in Figure 6-7.

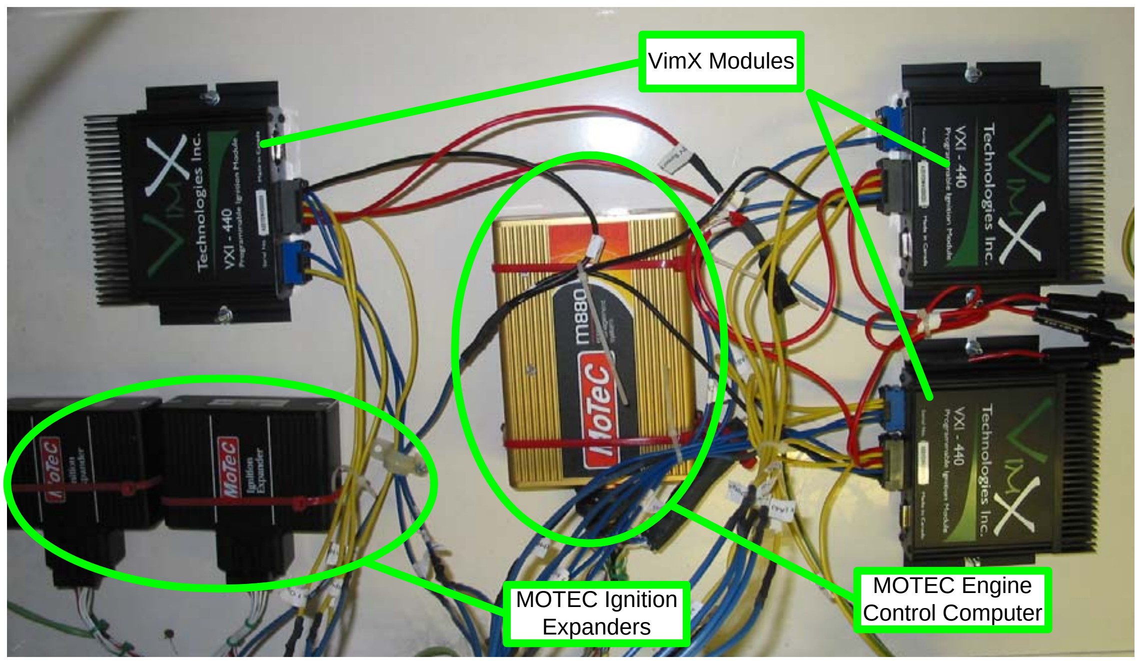


Figure 6-7. Labeled VimX Ignition System
Photo Credit: TIAX LLC

The VimX system is run as a slave to the Motec system, as discussed earlier. The Motec would supply the trigger signals to the VimX and, using the supplied software, the spark timing as well as thes spark durations and profiles could be altered. A screenshot of the VimX ignition control software is shown below.

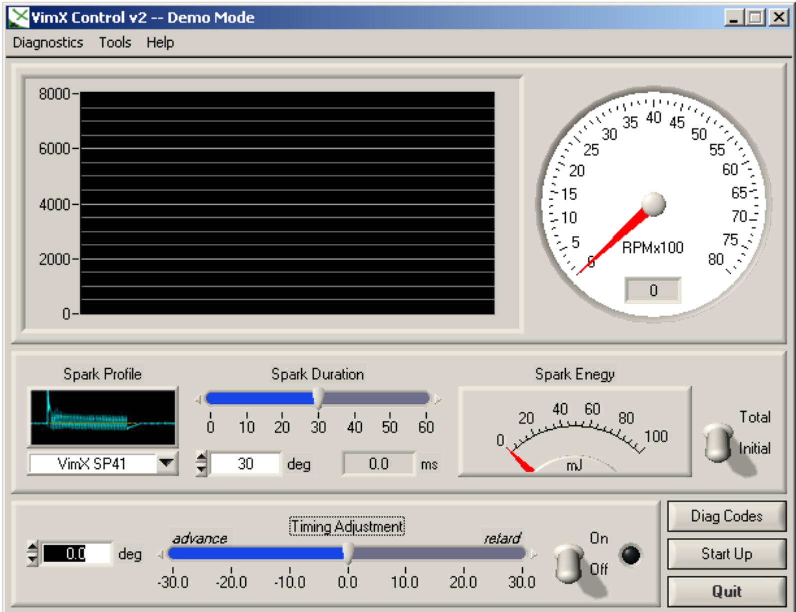


Figure 6-8. Screenshot of VimX Ignition System

Two systems were chosen to show a robust comparison. The Smartfire system was used and purchased for another project but proved to be useful during this test. One caveat with the Smartfire system was that the pencil coil design prohibited the use of the pressure-sensing spark plug, so power output was used as a means to determine combustion reliability (as may be seen from Figure 6-9).

Smartfire Coil

Standard Ford Coil

Figure 6-9. Comparison of Smartfire Coil to Ford Coil

Using this test setup, a series of tests were run to explore the effect of the higher energy ignition systems. The theory behind using higher energy ignition systems is that, even though the supplemental hydrogen greatly increases the ignitability of the mixture in the cylinder, the high dilution still present difficulties for ignition. A higher energy ignition system has the potential to overcome this difficulty, allowing leaner and more dilute mixtures, thus reducing the thermal NOx production. The effect of these systems are shown below.

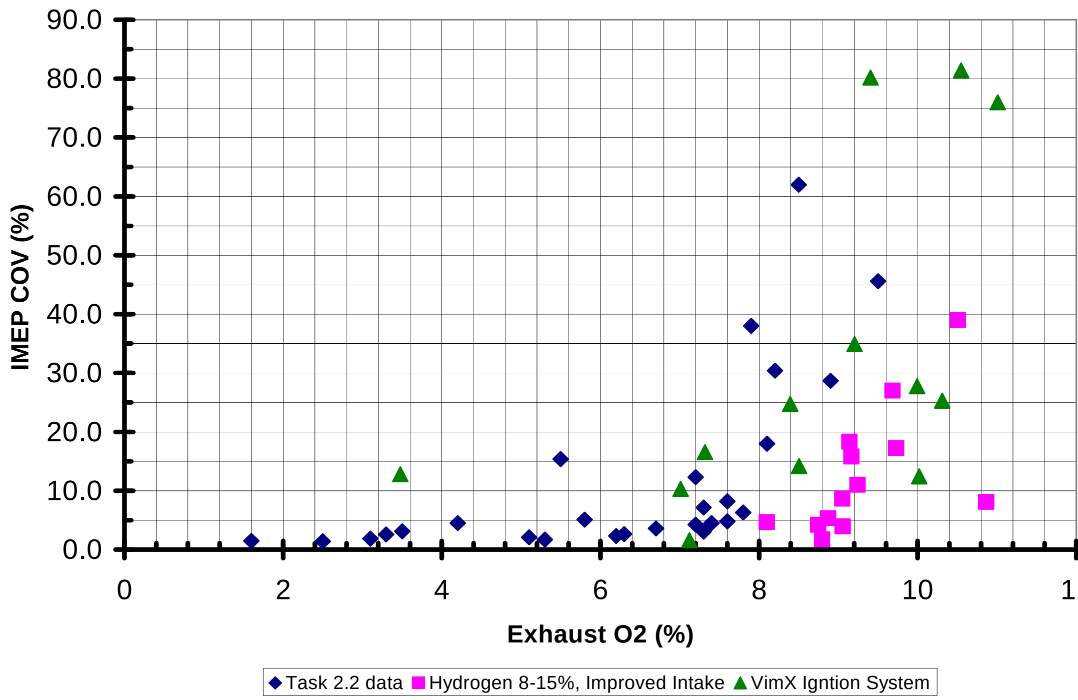


Figure 6-10. Comparison of VimX Ignition System with Standard

As may be seen from the green triangles in Figure 6-10, the high-energy VimX ignition system does not appear to have a beneficial effect on the IMEP COV for lean operation. Even though the system supplies additional energy, most of the data points fall right into the data scatter of the standard system, and some VimX data points on IMEP COV (%) are higher. The Smartfire system is left out of this graph because the pencil coils did not allow the measurement of in-cylinder pressure due to their design interfering with the spark plug pressure transducer. The Smartfire effects (or lack thereof) may be seen when the emissions data is taken into account. This is shown in the following figure (Figure 6-11).

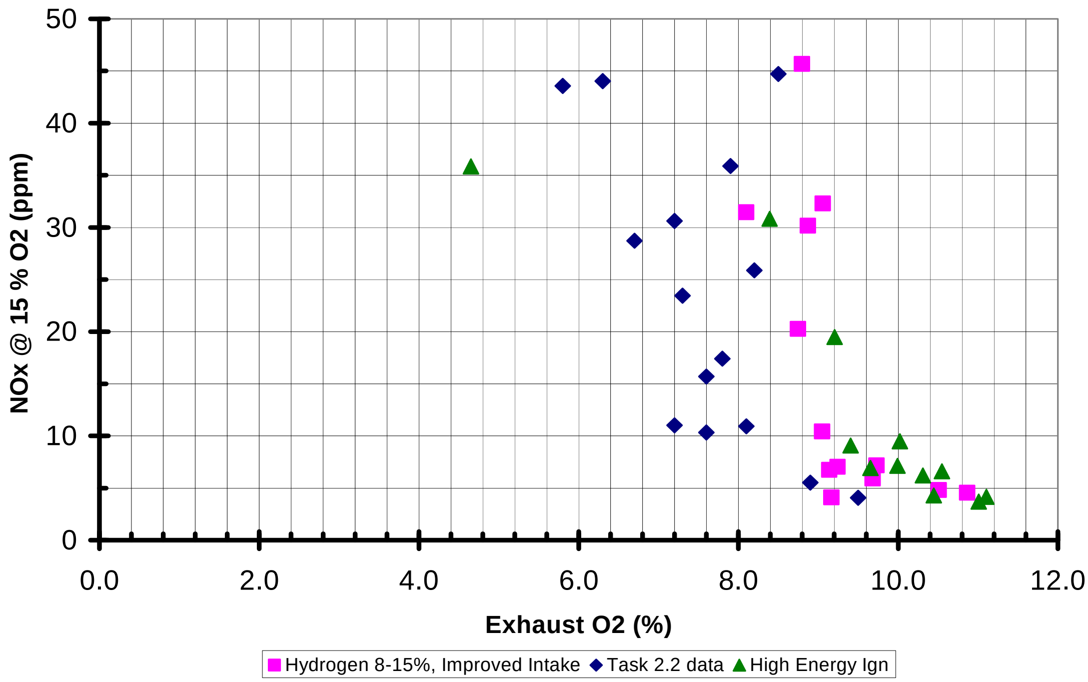


Figure 6-11. Effect of High Energy Ignition System on NOx Emissions

A similar effect is seen when both the VimX and the Smartfire ignition points are plotted with respect to their and NOx reduction capabilities. From Figure 6-11, the green triangles, which represent the higher energy ignition systems, fall among the data from the prior exploration, suggesting that the increase in ignition energy provided by these systems does not alter the cycle variability for extremely lean mixtures, and thus not allowing further NOx reductions.

Table 6-9. Summary of Lowest NOx Results for Higher Ignition Energy Tests

IMEP (bar)	IMEP COV (%)	NOx (Corrected to 15 % O_2) [ppm]	NOx (g/bhp hr, 15% O_2)	NOx (lb/MW hr)	H_2 LHV/CH_4 LHV
4.5	80.2	9	0.270	0.80	7.8%
6.8	34.9	19	0.334	0.99	13.1%
3.6	76.0	4	0.119	0.35	14.1%
6.2	27.8	7	0.122	0.36	14.4%
6.8	12.4	9	0.144	0.43	14.7%
6.2	25.3	6	0.104	0.31	14.7%
4.0	81.4	7	0.195	0.58	9.6%
N/A	N/A	7	0.110	0.33	11.0%
N/A	N/A	4	0.089	0.26	13.5%
N/A	N/A	4	0.076	0.22	14.2%

As may be seen from Table 6-10, the results from the high-energy ignition systems are not very impressive. Although some points have very low NOx omissions, the combustion stability is unacceptable. Thus, it appears that the high-energy ignition systems did not have the desired effect on the system.

6.5.3. EGR Systems Test Results

This section will deal with exhaust gas recirculation and how that affected the NOx emissions. EGR has a marked effect on the in-cylinder temperatures because the water and the carbon dioxide present in the engine exhaust both have high specific heat, and the water will vaporize, further decreasing the cylinder temperature. A caution with EGR is that because it is from the engine exhaust, it is high temperature, which could have the opposite of the desired effect on the NOx production. Thus, for the EGR set up in this project, the commercially available EGR cooler was used from the Ford Powerstroke diesel. The cooling medium for this cooler was engine coolant. This cooler was used in both of the EGR systems tested. The first EGR system tested was in the high-pressure loop of the system, meaning that the EGR induction point was after the compressor of the turbocharger. Since EGR is driven by a pressure differential, it was necessary to introduce a Venturi to drop the intake pressure enough to allow the exhaust gas to flow from the exhaust manifold into the intake manifold through the EGR cooler. For the sizing of a Venturi, values were used from the literature for the optimum ratio of the throat diameter to the pipe diameter. To verify the selection, a computational fluid dynamics model was made of the Venturi to assure that the pressure drop from the exhaust manifold to the throat of the Venturi would be adequate to allow enough EGR to circulate into the engine intake.

The results of the CFD simulation are shown below in Figure 6-12.

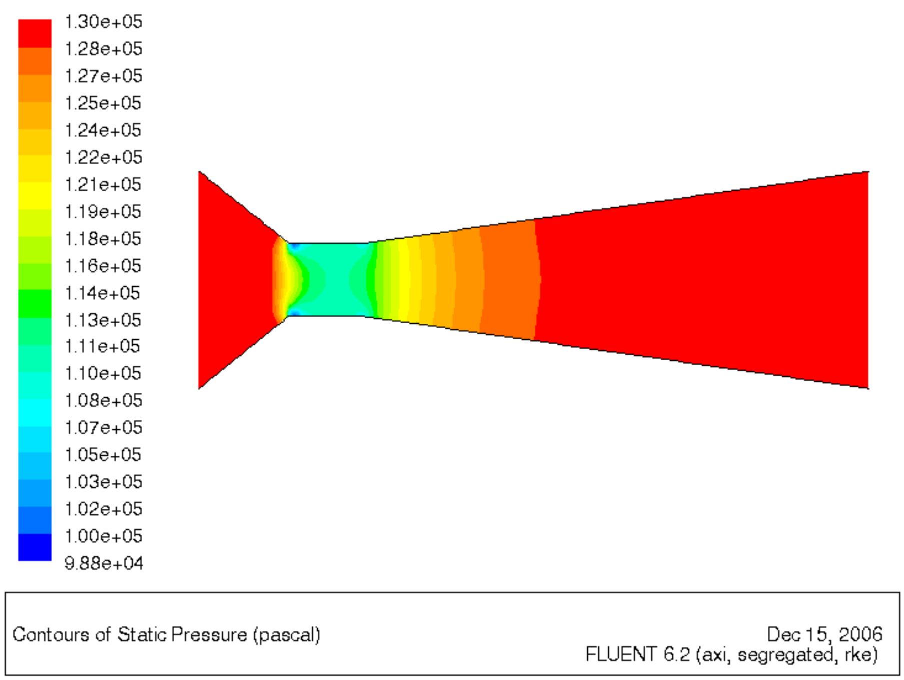


Figure 6-12. Pressure Contours for the Selected Venturi

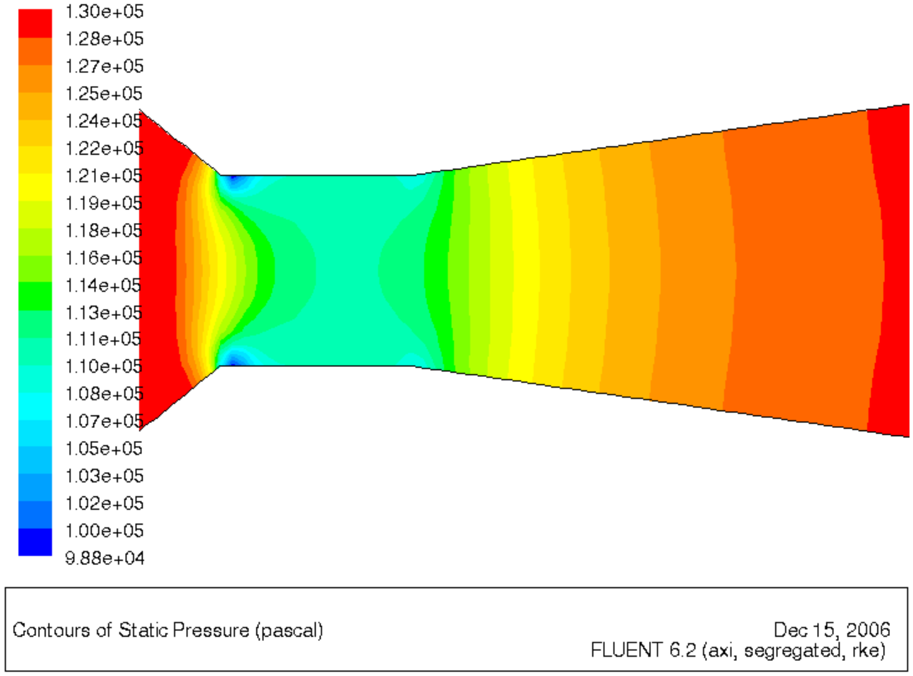


Figure 6-13. Close Up of Venturi Throat

As can be seen from the figure, the pressure drop across the entire Venturi was minimal. This case was run for a typical case where the engine flow rate was 120 g /s of air and the boost pressure was 130 kPa. A close-up of the throat of the Venturi, shown in Figure 6-13, shows that the pressure in the throat was right around atmospheric, which was adequate pressure to allow for the EGR to flow from the exhaust system, which is typically at 30 kPa above atmospheric when the waste gate of the turbocharger is fully closed.

A photograph of this setup is shown below.

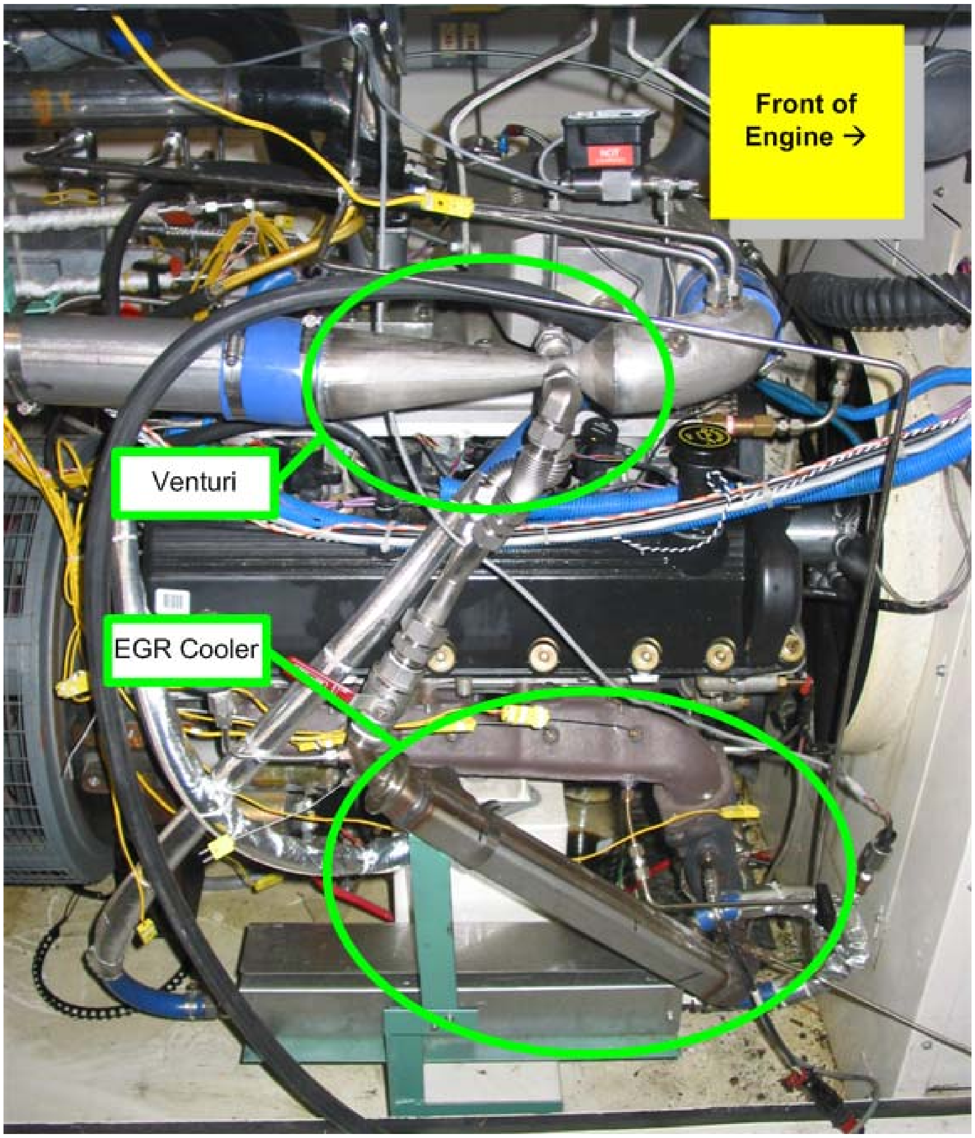


Figure 6-14. Photograph of High-Pressure Loop EGR System
Photo Credit: TIAX LLC

The inlet to the EGR cooler was tapped right into the exhaust manifold prior to the turbine of the turbocharger. The exhaust then flows to the cooler, where it was regulated by a ball valve before being introduced circumferentially into the throat of the Venturi. The advantage of introducing the EGR in this method was that the compressor of the turbocharger did not have to do work on the exhaust gases.

In addition to this method, an alternate method was used where the EGR was introduced before the turbocharger. This method was attempted for the maximum EGR rate. A photograph of the engine with this setup is shown below in Figure 6-15.

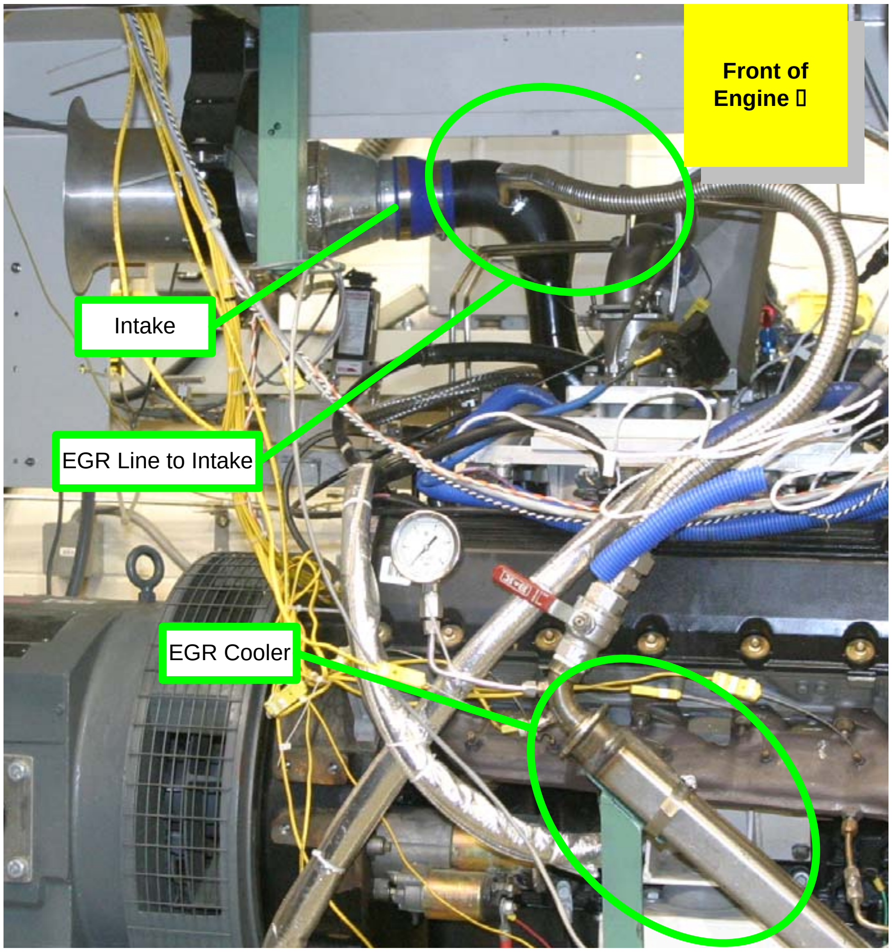


Figure 6-15. Photograph of second EGR setup
Photo Credit: TIAX LLC

In this setup, the same EGR cooler was used, but the outlet of the EGR cooler went directly to the engine intake, as may be seen from the photograph. The intake in this setup was much shorter because of the direct geometry, but had the disadvantage of having to compress the EGR as well as the air in the turbocharger. Since both systems resulted in EGR been introduced into the engine, no distinction was made between the two systems in the results analysis.

The effectiveness of the EGR cooler is shown below. During these tests the coolant was at an average of 80°C. It can be seen that, for the lower flow rates of EGR, the exhaust gas came close to the coolant temperature, but for the higher floor rates of EGR, it did not get cooled down as much. However, a significant temperature drop was observed through the EGR cooler, which was beneficial to the combustion.

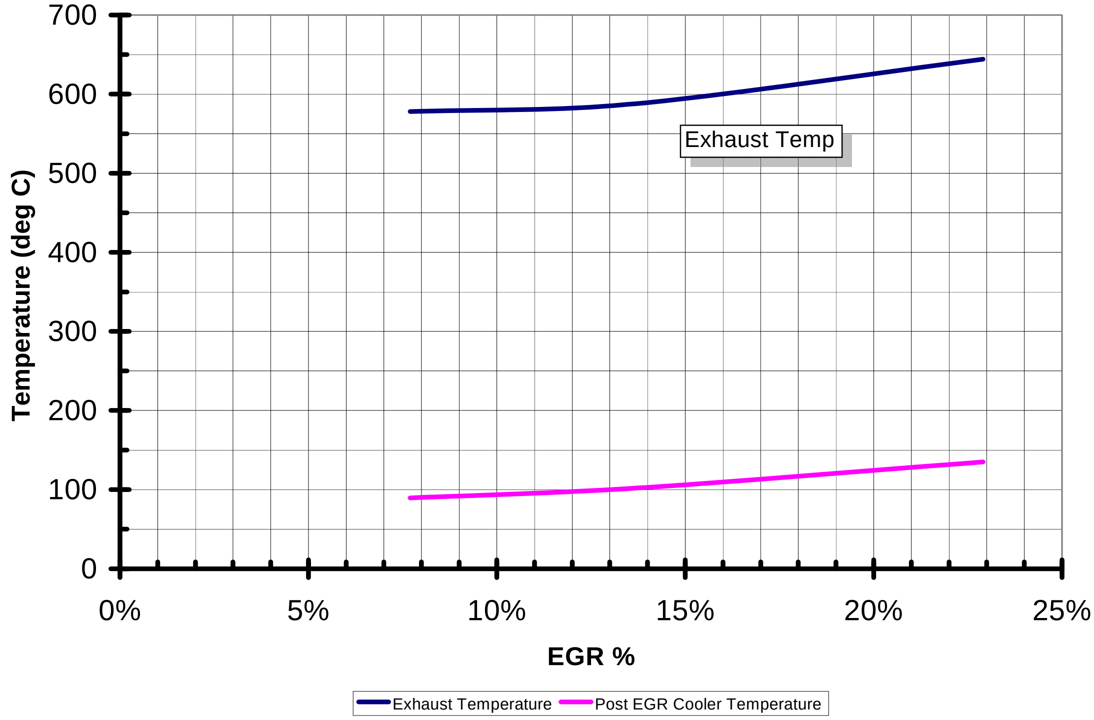


Figure 6-16. EGR Cooler Effectiveness

EGR had an interesting effect on the NOx emissions. This effect is shown in the context of the other explorations in Figure 6-17.

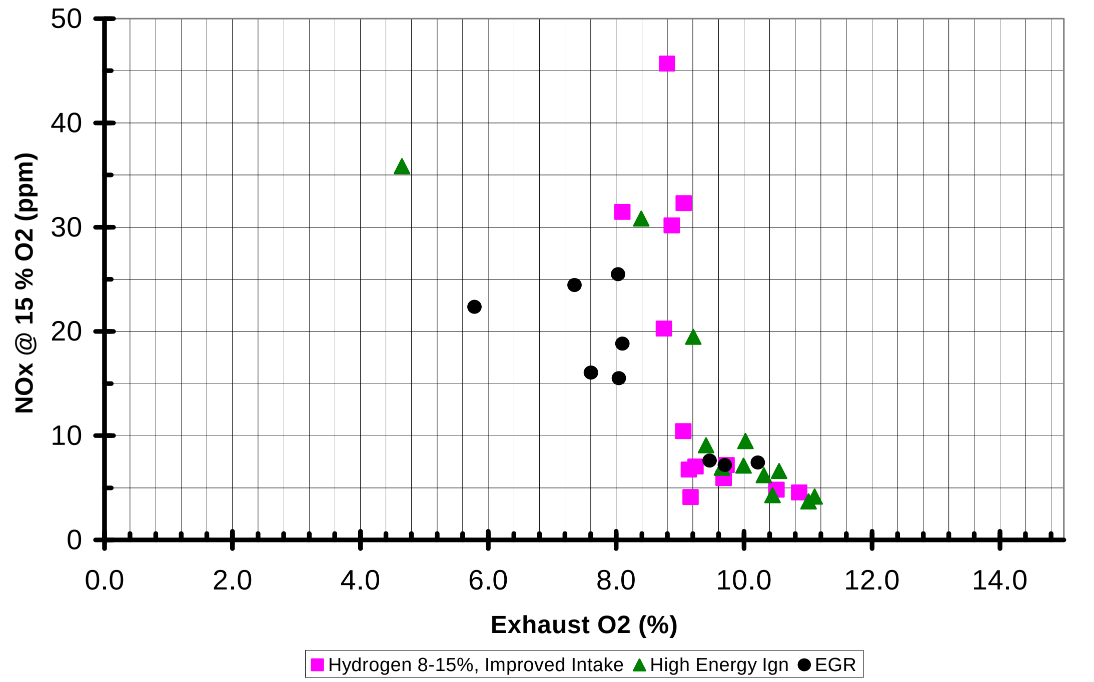


Figure 6-17. Effect of EGR on NOx

At lower oxygen concentrations, the EGR greatly reduced the thermal NOx formation, as the EGR points (represented as circles) are below the other points. However, at the higher exhaust oxygen concentrations, the EGR points fell right in among the excess air points. Thus, it appeared at extremely high levels of dilution with excess air, the NOx production was equivalently low to that of EGR supplementation. The best results are summarized below.

Table 6-10. Summary of Lowest NOx Points for EGR Tests

IMEP (bar)	IMEP COV (%)	NOx (Corrected to 15 % O_2) [ppm]	NOx (g/bhp hr, 15% O_2)	NOx (lb/MW hr)	H_2 LHV/CH_4 LHV	EGR (%)
6.1	8.7	8	0.044	0.13	10.7%	14%
5.9	5.1	19	0.122	0.36	15.5%	8%
5.9	3.7	7	0.047	0.36	14.7%	9%
5.96	1.7	16	0.100	0.14	14.7%	31%
7.7	16.4	24	0.191	0.30	10.5%	9%
N/A	N/A	7	0.089	0.56	10.6%	12%
N/A	N/A	22	0.114	0.26	13.5%	18%

The lowest NOx points are summarized in Table 6-10. It may be seen that the EGR did better than the higher energy ignition systems. Multiple points in the table contain excellent NOx readings as well as acceptable combustion stability.

6.5.4. Water Injection Test Results

Briefly examined in these tests was the effect of injecting water. Water was injected into the system prior to the throttle body using a misting nozzle. A photograph of the water spray is shown below.

Figure 6-18. Photograph of Water Spray
Photo Credit: TIAX LLC

The photograph was taken, for ease of experimentation, in a room environment (standard temperature and pressure). It can be seen that the spray breaks up into droplets extremely well. Inserting this nozzle into the engine would have the effect of narrowing the spray cone as air rushes by the nozzle. Since the manufacturer claims to have droplet sizes smaller than 30 μm, it is assumed that the majority of the droplets are entrained into the air stream and carried into the cylinders.

Plotting the water points on the graph with the rest of the data, the following figure is observed.

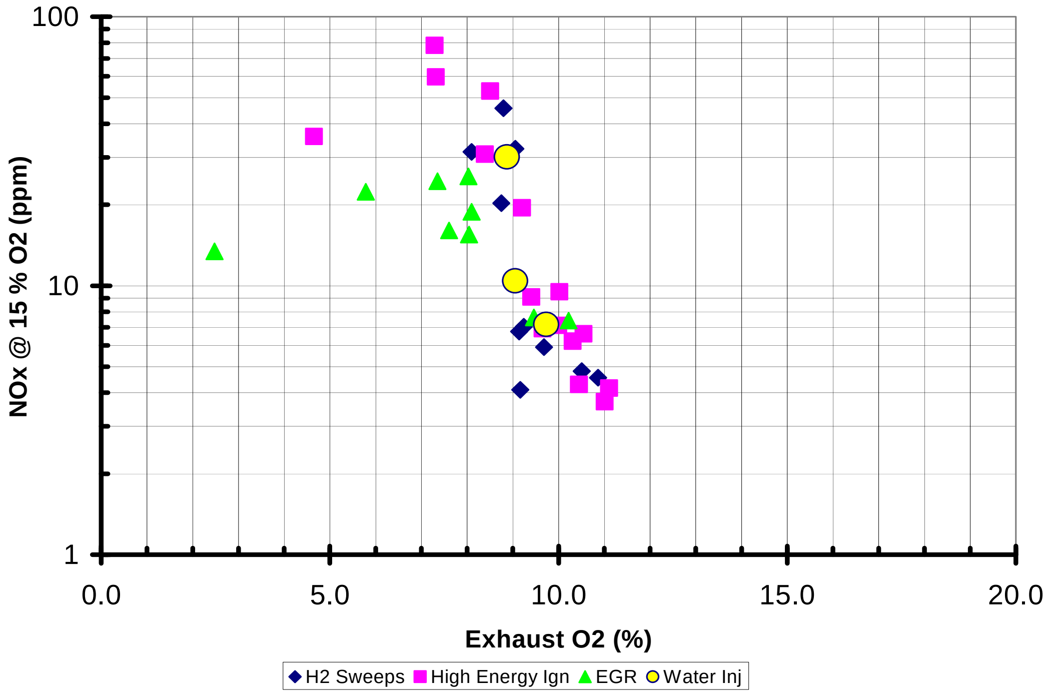


Figure 6-19. All corrected NOx data, including water injection points, as function of Exhaust O_2

The water points (shown as large blue circles) fall on top of the other points indicating that there was not a significant advantage to the injection of water, compared to other means of dilution. However, for a given dilution, the water did reduce the NOx emissions with minimal penalty.

Table 6-11. Summary of Water Injection Test Points

IMEP (bar)	IMEP COV (%)	NOx (Corrected to 15 % O_2) [ppm]	NOx (g/bhp hr, 15% O_2)	NOx (lb/MW hr)	H_2 LHV/CH_4 LHV	Water Flow (g/s)
7.1	5.3	30	0.338	1.00	8.9%	3
6.0	17.3	7	0.101	0.30	8.5%	1
6.6	8.7	10	0.142	0.42	7.5%	1

Despite the slight benefit, the water did not drop the NOx emissions enough to meet project goals.

6.5.5. Conceptual Process Optimization Overview

This report has detailed the results from a series of five experimental setups trying a range of four methods to reduce NOx emissions from an engine fueled with synthetic landfill gas. This section will endeavor to step back and look at the results as a whole from the series of tests over the experimental setups.

It is interesting to see the effect of hydrogen on NOx production. This is an indirect effect because hydrogen allows more dilution, but still is telling as to the results. Plotting a range of test points selected from all of the experiments during the conceptual process optimization results in the graph below.

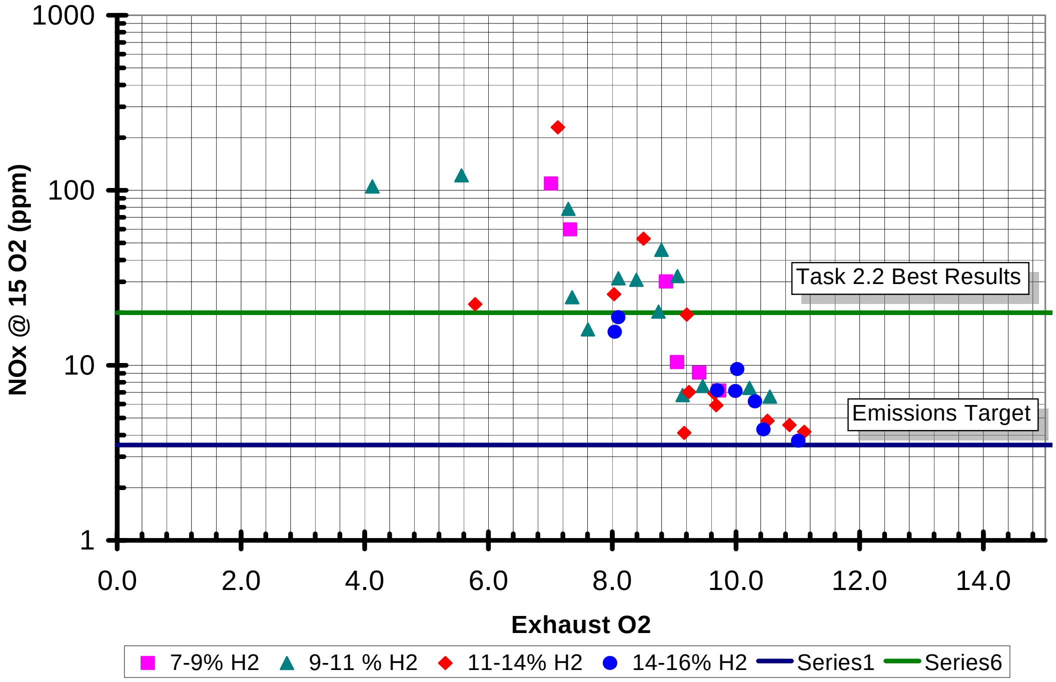


Figure 6-20. Comparison of all results showing effect of hydrogen addition

The higher amounts of hydrogen concentration are shown as the blue circles. At the higher exhaust oxygen concentrations (9-10% O_2), where dilution is the highest and hydrogen is necessary for combustion to occur, are where the most points with higher hydrogen supplementation are located. Thus, from the standpoint of pure dilution and hydrogen supplementation, it appears from this result that the higher hydrogen supplementation is most useful in obtaining the lower NOx emissions.

An important issue to take note of with high dilution engines is not only the ignition in combustion stability, but also the burn durations. As more and more dilution is added to the cylinder, the flame front will have difficulty propagating, especially when the dilution products are not an oxidizer such as air. Hydrogen does much to counteract this because of its extremely high flame speed. The parameter to examine to determine burn time is the 10 to 90% duration, which is a measure which the combustion analysis program calculates to determine the time in crank angle degrees it takes for the combustion to proceed from 10% mass fraction burned to 90% mass fraction burned. The results of this are plotted as a function of oxygen concentration.

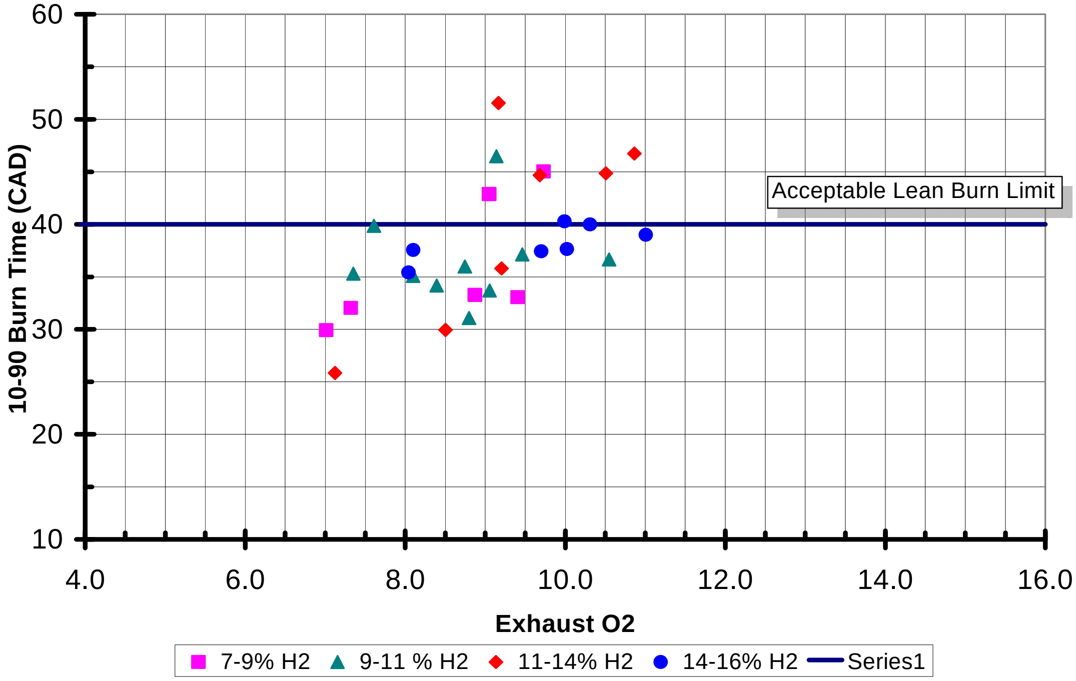


Figure 6-21. Burn Time as a Function of Exhaust Concentration

For a typical stoichiometric engine, the burn times are between 17 and 25 crank angle degrees. As the burn time increases, the flame stretch as it moves across the cylinder can become an issue. For engines that operate with more dilution, burn times less than 35 crank angle degrees are typical. However, it may be seen from this data that even though more hydrogen (thus increasing the flame speed) is added, the trend is still upward with respect to burn time increasing with increasing in-cylinder dilution. This suggests that even though the mixture can be ignited, more hydrogen may be necessary to decrease the burn time. This decrease in burn time will also lead to an increase in combustion stability as well as a decrease in cycle-to-cycle emissions variability.

Looking at the approaches as a whole, most of the approaches were effective in reducing the NOx production, even though the higher ignition energy systems did not improve the ignitability of the mixtures. A summary of all the points that show acceptable combustion stability or acceptable power output (in the case of the Smartfire system where combustion stability measurements were not taken) is shown below.

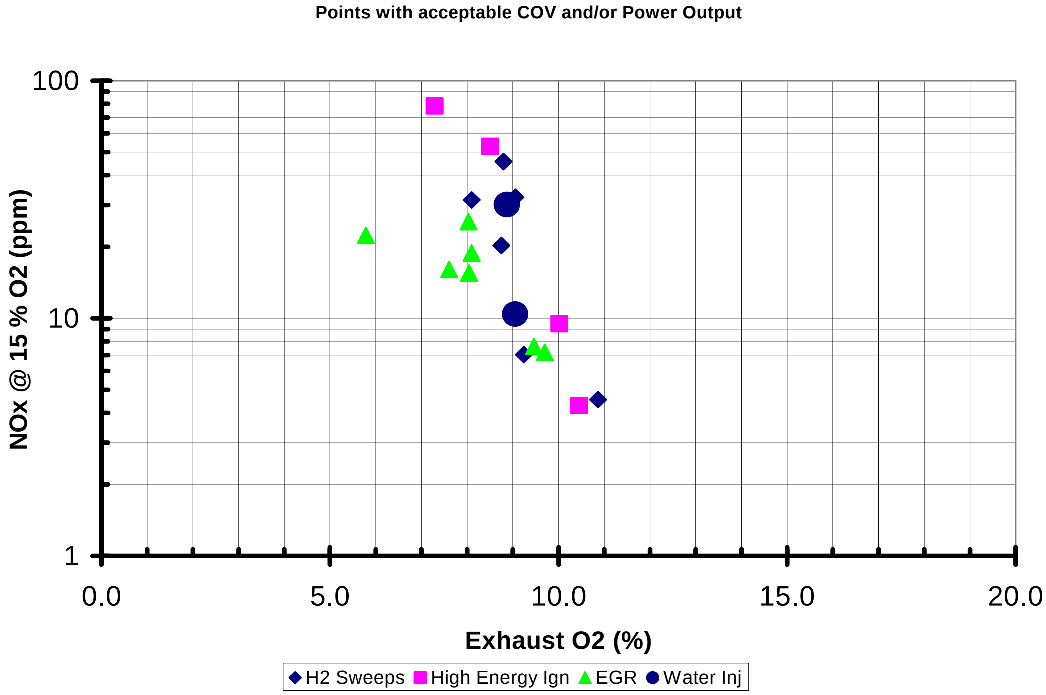


Figure 6-22. Summary of points with acceptable combustion stability

As may be seen from the above figure, the variety of approaches allowed for significant NOx reduction. The most effective method is the addition of more hydrogen, which allowed for the introduction of EGR or operating with more air dilution.

A summary of the lowest NOx points that still provided acceptable combustion stability is shown below in Table 6-12.

Table 6-12. Summary of low NOx points with acceptable combustion stability

IMEP (bar)	IMEP COV (%)	NOx (Corrected to 15 % O_2) [ppm]	NOx (g/bhp hr, 15% O_2)	H_2 LHV/CH_4 LHV	NOx (lb/MW hr), 15 % O_2
5.4	8.1	5	0.035	13.5%	0.10
6.9	11.0	7	0.044	11.4%	0.13
6.6	8.7	10	0.071	7.5%	0.21
6.8	12.4	9	0.078	14.7%	0.23
N/A	N/A	4	0.043	14.2%	0.13
6.1	8.7	8	0.044	10.7%	0.13
5.9	3.7	7	0.047	14.7%	0.14
6.6	8.7	10	0.071	7.5%	0.21

The NOx results as summarized in the above table show a significant reduction when compared to the results obtained in Task 2.2, so the methods of further NOx reduction suggested in the task 2.2 test report were effective. The results do come close to the project goals 0.032 g/bhp-hr or 0.07 lb/MW-hr but are still above those goals.

6.5.6. Extended Period Test Run

The extended period test run was carried out to examine the long-term stability of the process. The extended run highlights the need for closed-loop feedback for the engine control. Any time there is a NOx excursion, the cause can be easily correlated to the air/fuel ratio. The main reason for the air/fuel ratio excursions was the fuel supply, which was bottled natural gas stored in six packs of 300 ft3 bottles. The bottles are supplied at about 2000 psi pressure and are regulated down to 50 psi through a series of regulators at a high flowrate to supply the engine with fuel. Because of the Joule Thompson effect, as the gas is expanded, it cools. The supply gas temperature ranged from -60 to -40 deg Fahrenheit during the testing. For shorter test runs, this temperature (and thus the natural gas pressure/state) was steady, but over the longer test runs, the effect had to be manually compensated and caused the drift seen in the air/fuel ratio, leading to the drift seen in the NOx emissions.

The NOx emissions can be seen as a function of time over the extended run test in Figure 6-3. The variations, as mentioned earlier, are a function of the air/fuel ratio. Setup F was used during this test run. The test was done in the typical manner, and throughout testing the bottled gasses were switched as needed.

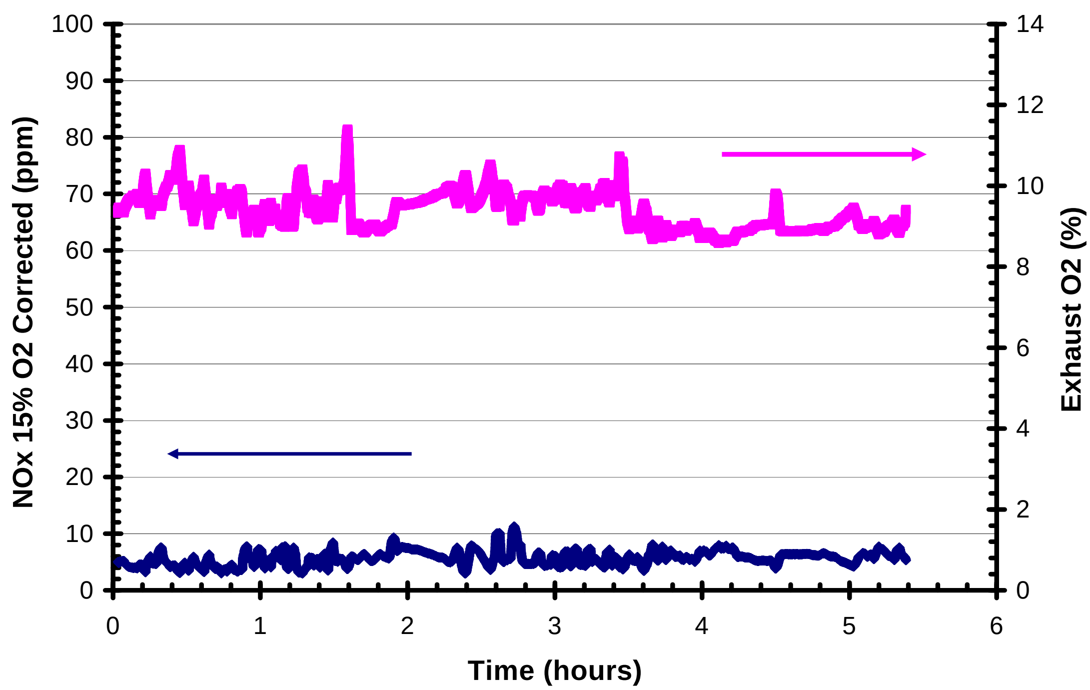


Figure 6-23. NOx Emissions and Excess Air During the Extended Test Run

Even though there are fluctuations, the histogram of the above data clearly shows that the excursions do not reflect the majority of the NOx emissions.

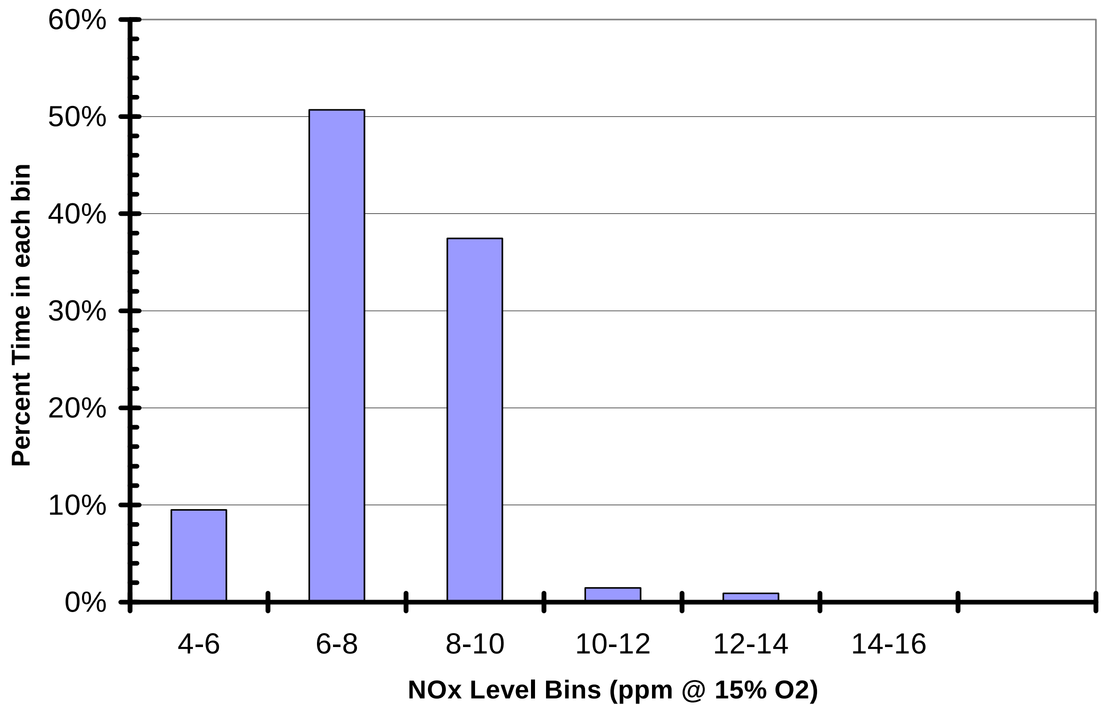


Figure 6-24. Histogram of NOx Data During Extended Time Test

As shown in the figure, the majority of test points were in the 6-8 ppm range, with the next highest amount in the 8-10 ppm range. The average over the entire test was 6 ppm, which corresponds to 0.042 g/bhp hr NOx, validating prior work.

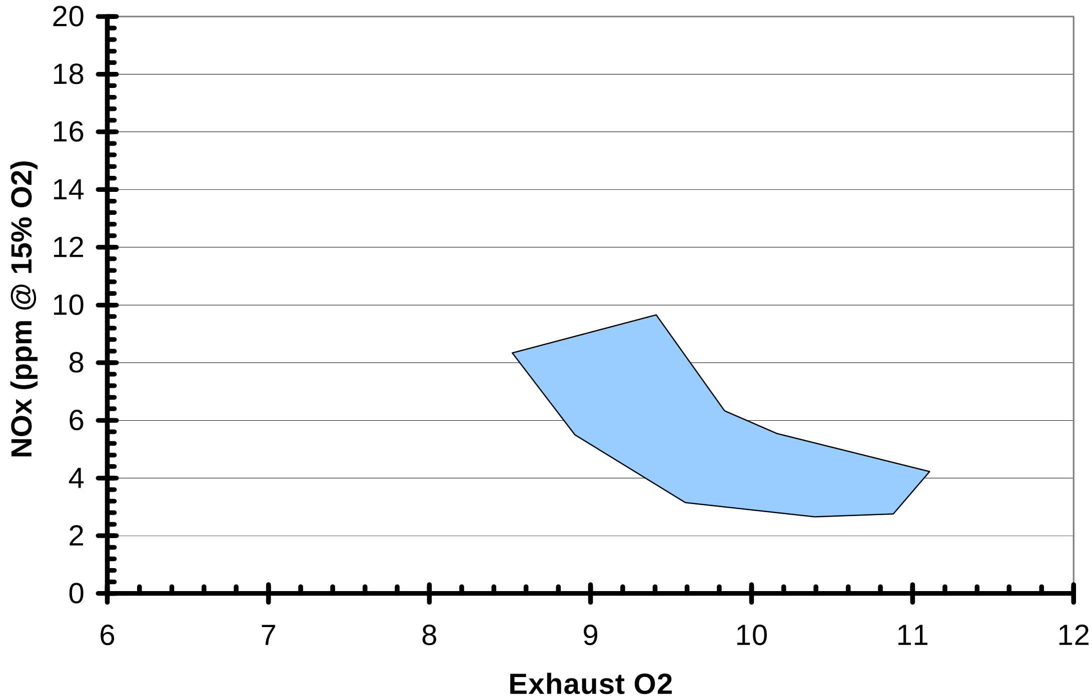


Figure 6-25. NOx Emissions Dependence on Exhaust O_2

Shown in the figure is the band of NOx emissions as a function of exhaust oxygen concentration. As the air/fuel ratio becomes leaner, the in-cylinder combustion temperature drops, lowering the thermal NOx production. This highlights the importance of excellent air/fuel ratio control, especially at these extremely lean air/fuel ratios. A summary of the entire test run is given below.

Table 6-13. Summary of Extended Test Run

Average Engine Power (kW)	Average O_2 (%)	Average T. HC, CO, CO_2	NOx (Corrected to 15 % O_2) [ppm]	NOx (g/bhp hr, 15% O_2)	NOx (lb/MW hr)	H_2 LHV/CH_4 LHV
55	9.4	1900 ppm, 0.06%, 6.9%	6	0.042	0.12	12%

6.6 Reformer and Heat Exchanger System Optimization

The test program was designed in such a way that the reformer/heat exchanger system design was optimized in parallel to the engine setup optimization, as the feedgas requirements of the hydrogen into the engine directly impact the required reformer performance.

One key issue for the reformer is the temperature of the reformed gases entering the engine, as that has a direct correlation to engine emissions. Shown below is a plot of intake temperature as a function of boost.

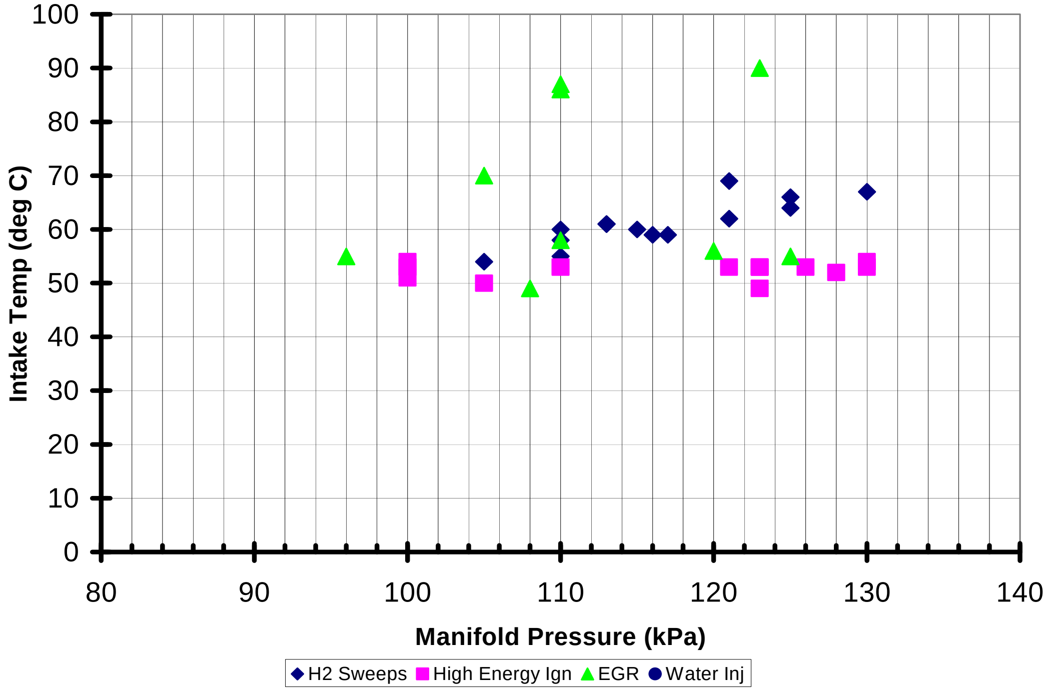


Figure 6-26. Intake Temperature as a Function of Boost

As may be seen from the above graph, which shows the temperature of the intake after the intercooler, the majority of points fall around 60°C. However, the hotter EGR points do raise the intake temperature to around 90°C. How this affects NOx production is shown in the figure below.

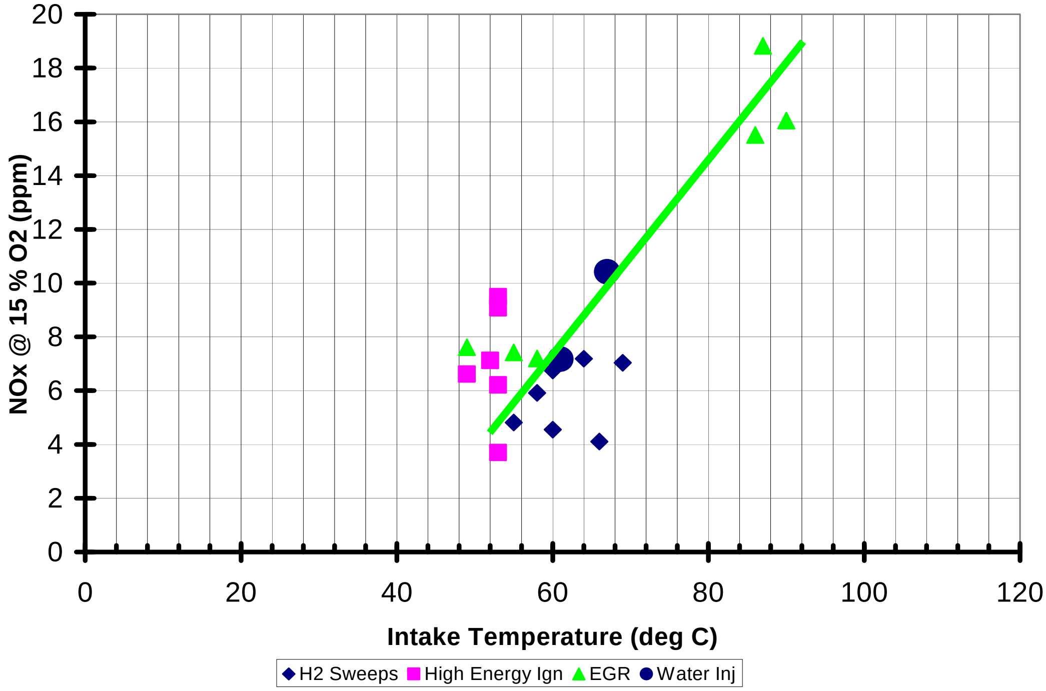


Figure 6-27. The effect of intake temperature on NOx at low emissions points

As may be seen from examining the above figure, all of the lower NOx points have an intake temperature below about 60°C. As the intake temperature goes up, this affects the NOx emissions. Thus, from a system design standpoint, it is desirable to design the intercooler of the engine to drop the reformate/air stream to below 60°C. Further cooling would drop the NOx; however, this would adversely affect efficiency and cost.

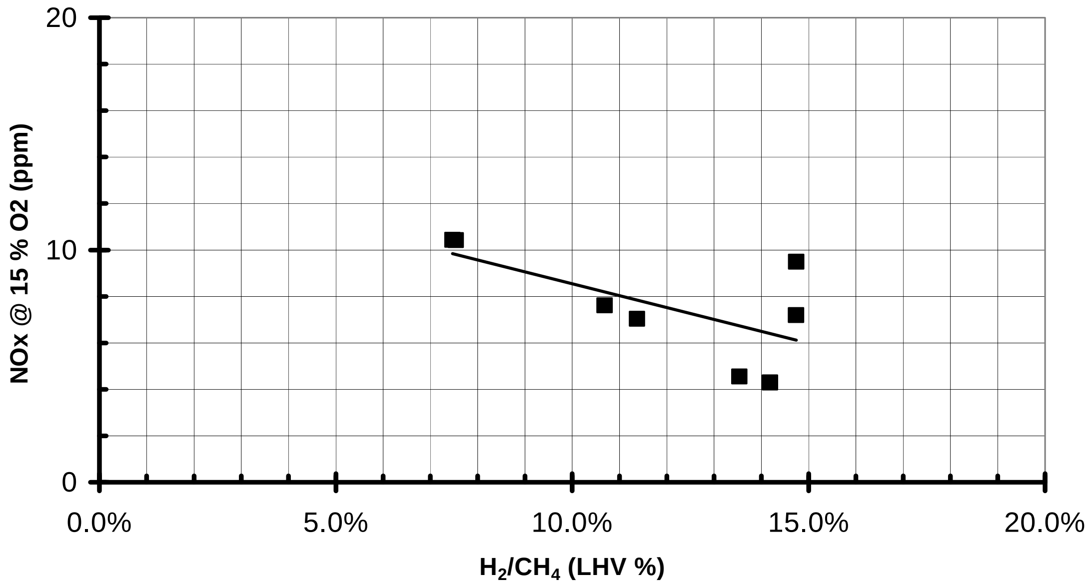


Figure 6-28. The Impact of Hydrogen Supplementation

Looking at the points from the low NOx runs in Figure 6-28, it may be seen that in the data scatter it appears that increasing the hydrogen supplementation above 10% does not improve the NOx reduction significantly, while the cost and size of the reformer and heat exchangers scales with hydrogen. Therefore, the recommended hydrogen supplementation rate is 10% H_2/CH_4 LHV.

Thus, from the BioHALO system perspective, the minimum reformer specifications are summarized below as based upon the results of Task 2.3:

Table 6-14. Summary of Acceptable Reformer Parameters

Parameter	Value
Total Reformer Flow Rate for this engine power rating	900-1000 SCFH
Acceptable reformate/air post-intercooler temperature	60 deg C or less
Necessary H_2 concentration in reformate	28 %
System Pressure	Atmospheric
Duty Cycle	Reformer must follow engine load to maintain 10 % LHV H_2/CH_4 up to 100% load

6.7 Results and Recommendations based on Task 2.3 Test Results

Based upon the recommendations from the Task 2.2 test report, this series of tests in Task 2.3 have been successful in improving the emissions performance of the engine. However, emissions levels are still slightly above the proposed goals. Following is a list of the conclusions and recommendations from this round of testing:

- The improved mixing provided by the intake redesign in addition to the higher amounts of hydrogen supplementation proved effective in reducing the engine emissions.
- The ignition system, when switched to high-energy options, did not show a particular improvement in performance or emissions. A further concern noted during this Task was that even though ignition was achieved of the mixture, the burn times are slightly longer than desirable, leading to cycle-to-cycle variability.
- Water injection was interesting in that it allowed for lower NOx emissions when compared to a standard point of similar dilution but did not improve the emissions to the point beyond emissions targets.
- Because this was a test plan designed to encompass a range of operating conditions, each point was short to finish all of the testing required in the given amount of time. To prove the value of the system, it would be desirable to run for a much longer period.
- Although NOx targets were not met, the results show an impressive emissions reduction for a reciprocating engine technology. For example, BACT for a Hess Microgen stoichiometric natural gas engine with a three way catalyst is 0.07 g/bhp-hr, and this project demonstrated multiple points 50-67% of this value *engine out.*
- It would be interesting to explore using hydrogen supplementation as an enabler for high load/high dilution pre-mixed charge ignition concepts. The hydrogen supplementation was able to light off, but work could be done to improve its combustion stability as well as improve burn durations. Using a high-energy micro-pilot or compression ignition might answer the two concerns raised in this task and provide the dilution necessary for even lower NOx.

7.0 Results of BioHALO System Conceptual and Detailed Design

Task 2.4 of the project covered the Conceptual Design of a generic BioHALO system, which includes a LFG “slipstream” reformer feeding hydrogen-rich reformate fuel gas (blended with the balance of the LFG) to the engine. The design is based on the most promising configuration of BioHALO determined from the Task 2.3 optimization tests.

Key features of the system for successful efficient low-NOx operation include (a) energy management of the reformer using heat exchangers and (b) lean-burn set-up of the engine (excess air, boost, high energy spark, and low manifold air temperature).

This section is organized as follows: ***Section 7.1*** includes a discussion of the design basis and discussion of evaluations and tradeoffs considered. ***Section 7.2*** is a summary of the system specifications for the BioHALO based on Task 2.3 optimization studies. These specifications will address the following:

- IC engine
  - Target A/F ratio
  - Required reformate mix ratio
  - Spark timing and type of ignition system
  - Intake manifold temperature
  - Intake manifold pressure and type of turbocharger
- BioHALO reformer
  - Required total flowrate
  - Acceptable reformate temperature range
  - Needed reformate hydrogen concentration
  - System pressure
  - Duty cycle
  - Recommended heat exchangers to avoid excess fuel use or electric power
- Exhaust oxidation catalyst (if required to meet targets for CO and VOC engine-out emissions)
  - Engine exhaust temperature range
  - Engine exhaust flow rate

- Engine exhaust CO and VOC concentration
- Conversion efficiency needed
- Durability expectations including siloxane tolerance

- Controls
  - Control algorithm type
  - Number of control outputs and sensor inputs needed
  - Sensor requirements

Section 7.3 describes the detailed heat and mass balances for BioHALO including chemical reactions of the hydrogen generator (reformer) and the heat exchangers. ***Section 7.4*** presents the package of schematic drawings, diagrams, and parts lists as follows:

- Process flow diagrams
- P&IDs
- Controls schematics
- Equipment and layout sketches
- Preliminary equipment lists

Section 7.5 of this Conceptual Design section includes a discussion of operating strategies to employ and resulting performance expectations. The Conceptual Design Report is intended to be used as a foundation for specific detailed designs of BioHALO systems for various power levels depending on the anticipated LFG volume flow rate.

7.1 Design Basis of BioHALO System

7.1.1. Engine Operating Parameters for Optimization of NOx

Scoping tests were conducted using synthetic reformate on an instrumented landfill gas engine rated at 75 kW at the TIAX engine test laboratory. Most runs were carried out with the engine operated at 45-55 kW to operate sufficiently lean to achieve low NOx with H_2 addition. In this initial phase of the development effort, engine operation and emissions performance data needed to be developed with the eventual demonstration engine/ generator fueled with synthetic LFG combined with synthetic reformate having a composition similar to that expected to be produced by the eventual ATR placed at the site. Using a mixture of 57% natural gas, 23% CO_2, and 22% N_2 as the synthetic LFG reformate, the leanest point the baseline engine could be operated at was 4.2% O_2 in the exhaust (***without hydrogen***), after which the combustion stability deteriorated. This corresponded to about 25% excess air. At this point, the engine-out humidity corrected NOx was 440 ppm, which corresponds to 1.8 g/ihp-hr NOx (2.2 g/bhp-hr NOx or 6.9 lb/MW-hr).

The next set of tests (Task 2.2) was designed to determine the effect of adding synthetic reformate, which was 52% H_2 and 48% CO. Adding this synthetic reformate mixture allowed the engine to have stable combustion out to ~8 % O_2 in the exhaust at a minimum addition rate of **6% H_2**/CH_4 (on a LHV basis). This corresponded to 62% excess air. Addition of further hydrogen increased the combustion stability marginally, but it still did not allow the engine operating limit to be extended beyond 8% O_2 in the exhaust. At this operating condition, humidity corrected **NOx was 20 ppm**, which corresponds to 0.12 g/ihp-hr NOx (0.15 g/bhp-hr or 0.47 lb/MW-hr), a reduction of over 93% compared to the baseline case.

The next set of tests (Task 2.3) were designed to use high energy spark and EGR to optimize the excess air to minimize NOx by adding even higher levels of hydrogen (synthetic reformate). Adding this level of hydrogen (10-14% by energy) allowed the engine to have stable combustion out to ~10-11% O_2 in the exhaust at a minimum addition rate of **10% H_2**/CH_4 (on a LHV basis). This corresponded to 100% excess air. Addition of further hydrogen increased the combustion stability marginally, but it still did not allow the engine operating limit to be extended beyond 10-11% O_2 in the exhaust. At this operating condition, humidity-corrected **NOx was 7-8 ppm (4-5 ppm NOx corrected to 15% O_2)**, which corresponds to 0.05 g/ihp-hr NOx (**0.055 g/bhp-hr or 0.17 lb/MW-hr**), a reduction of over 97% compared to the baseline case. ***This represents a significant reduction over the best LFG fired lean-burn prechamber engines, whose levels are 0.4 g/bhp-hr***, but still was 25% above the proposal target of 0.032 g/bhp-hr NOx (0.10 lb/MW-hr). The 98% reduction in engine-out NOx has been demonstrated using an in-line turbulent mixer and high-energy spark system.

7.1.2. Design Basis for BioHALO System

Based on the test program summarized above, the key BioHALO process parameters are as follows:

- LFG Engine operated at 100% excess air (10% O_2 in exhaust) with high energy ignition system
- Engine turbocharged to at least 0.5 bar intake manifold above atmospheric, and aftercooled to maximum intake manifold temperature 40°C.
- Landfill gas reformer sized to supply hydrogen at 10% of the methane flow rate by energy (33% by volume H_2 in total H_2 plus CH_4). This implies that approximately 15% of the LFG flow is diverted to the reformer to produce hydrogen. (The reformer also produces CO fuel value at 22% volume CO per volume of hydrogen; therefore the fuel value of the CO adds 26% to the H_2 fuel value).
- NOx emissions controlled to 0.032 g/bhp-hr (0.10 lb/MW-hr) by virtue of specifications 1, 2, 3 above.
- System efficiency accounting for reformer thermal management must be within 2% of baseline without BioHALO.

- Ability to follow variable load same as conventional LFG engine while maintaining 10% O_2 in the exhaust and proportional hydrogen flow from reformer at 10% of methane flow rate by energy.

- Oxidation catalyst reduces engine-out UHC and CO emissions to under 10 ppm.

The BioHALO system schematic is shown in Figure 7-1 below.

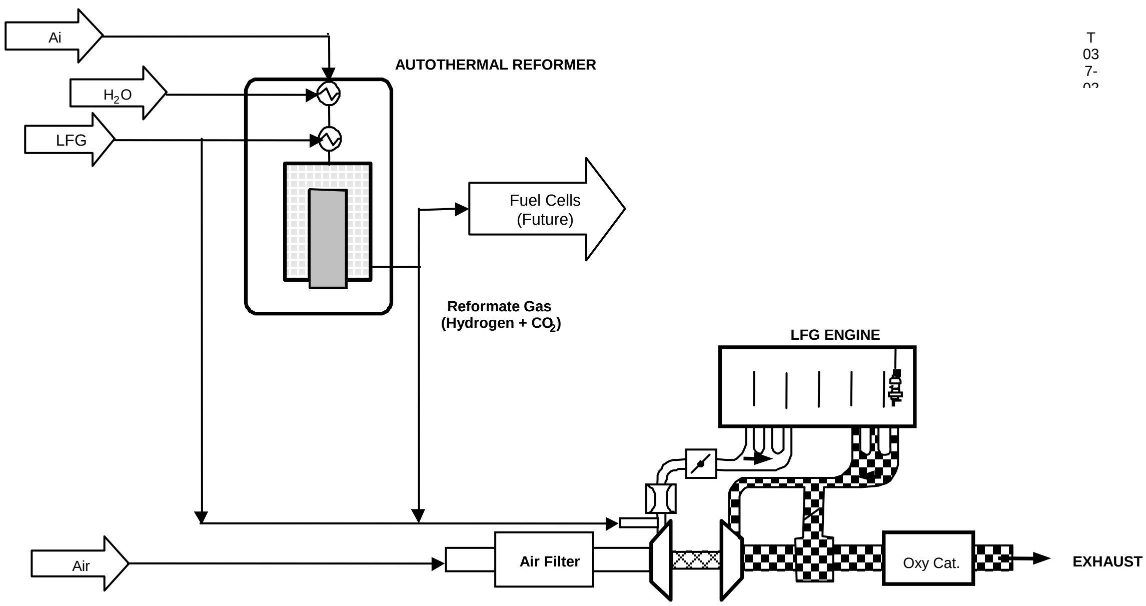


Figure 7-1. Schematic of BioHALO System

Reformer operating conditions: Not shown in this figure is the type of reformer or operating conditions such as air-fuel ratio or light-off temperature. After considering several types of reformers (partial oxidation, steam reforming, etc) we selected the auto-thermal reformer operating at equivalence ratio 3:1 (200% excess fuel). This reformer can be designed around a low cost catalyst similar to an automotive three-way catalyst, and is slightly exothermic (adiabatic temperature rise of about 200°C between inlet and outlet). For catalyst light off, the inlet gases must be at 600°C. The reason that the authors avoided steam reforming is that the addition of a small steam generator (boiler) was seen to be problematic in terms of maintenance, plugging and fouling, etc.

Need to cool down the reformate fuel gases: The reformate gas (H_2, CO and inerts) exits the reformer at about 800°C and must be cooled down to at least 140°C before remixing with the 85% main stream of LFG fuel. Otherwise air breathing would be impacted and engine power would suffer.

Need for preheat and sources of preheat: Three gas inlet streams must be preheated to enter the reformer at 600°C (about 1100°F); the LFG itself, the water vapor (steam) required, and the air supply to the reformer. Even at only 15% of the LFG flowrate, the LFG-slipstream preheat represents a significant heat demand. The design calls for using two sources of heat:

- The exhaust gas exits the turbocharger intercooler at about 550°F (250°C) and still contains about 14% of the original fuel energy. Therefore exhaust gas can be used to (a) preheat water to 100°C before creating steam for the reformer, (b) partially preheat the air to the reformer, say up to 200°C, and (c) preheat the LFG slipsteam up to 200°C .
- Hot reformate gas must be cooled and over 25,000 BTU/hr is available. The design assumes that we run a counter-flow heat exchanger to further preheat the LFG slipsteam from 200°C to 600°C (this absorbs 4300 BTU/hr), to further preheat air from 200°C to 600°C (this absorbs 5900 BTU/hr), and to vaporize water and raise the steam to 600°C (this absorbs 12,500 BTU/hr).

Need LFG Burner for start up: Since start up of the reformer with the above two sources of heat is not feasible, a small burner was included to provide steam and to preheat the reformer catalyst to light-off temperature. About 100 BTU/hr LFG input rate or 10% of the engine fuel input is sufficient for an 80 kW engine generator, according to the calculations (see below).

The heat exchangers must be designed for low pressure drop so as to not reduce engine efficiency.

Need oxidation catalyst.

7.2 System Specifications of BioHALO system

Based on the design considerations outlined above, system specifications were developed for the BioHALO system. The specifications are as follows:

1. IC engine

    - Target A/F ratio: 100% excess air.
    - Required reformate mix ratio: 10% hydrogen to methane by heating value.
    - Spark timing and type of ignition: High energy ignition 20° BTC.
    - Intake manifold temperature: Maximum 60°C.
    - Intake manifold pressure and type of turbocharger: 0.5 bar boost, Garrett.

2. BioHALO reformer

    - Required total flow rate: 900-1000 SCFH for 80 kW.
    - Acceptable reformate temperature range 700-900°C at outlet.
    - Needed reformate hydrogen concentration 28% minimum by volume.
    - System pressure: Atmospheric.
    - Duty cycle: 100% operation following engine load.

- Requires heat exchangers to preheat feed streams to 600°C; this avoids excess fuel use or electric power.
- Inlet levels of sulfur-containing gas below 10 ppB to avoid poisoning; requires activated carbon trap or sulfur tolerant catalyst.

3. Nitrogen Oxide Emissions

- As a result of specifications #1 and #2 above, the NOx emissions will be 0.032 g/bhp-hr (0.10 lb/MW-hr).

4. Exhaust oxidation catalyst (required to meet targets for CO and VOC engine-out emissions).

- Engine exhaust temperature 280°C and flow rate 200 SCFH per kW rated power.
- Engine out exhaust CO 1000 ppm and VOC concentration 100 ppm.
- Conversion efficiency 99% or better.
- Durability 4,000 hours (replace cartridge).

5. Controls

- Control algorithm type: Feedback control off H_2 concentration sensor and exhaust gas oxygen sensor.
- Control outputs for feed stream flow rates and mix of LFG, air and steam to the reformer. Sensor inputs needed include exhaust oxygen, hydrogen content of reformate, total reformate gas flow rate.
- Sensor requirements: flow meters, thermocouples, species concentration.

7.3 Heat and Mass Balance for BioHALO system

In this section the authors describe the detailed heat and mass balances for BioHALO including chemical reactions of the hydrogen generator (reformer) and the heat exchangers. The generic LFG engine generator is assumed to be rated at 80 kW with a heat rate of 10,000 BTU/kWh, which corresponds to 34.1% efficiency. The landfill gas is assumed to consist of 55% methane, 22.5% carbon dioxide, and 22.5% nitrogen for simplicity.

The LFG input stream is split 15% LFG to the reformer and 85% LFG to the main engine (after it is remixed with reformate). The reformer is fed by steam, LFG, and air at stoichiometric ratio corresponding to 200% excess air. All feed streams must be preheated to 600°C and the energy transfers to accomplish this are developed in Table 1. The exhaust gas of the engine post-turbocharger is assumed to be at 280°C and is used to preheat all feed streams to 200°C using a two-stage heat exchanger. The reformate gas exits the autothermal reformer at 800°C and is used to further heat all feed streams to 600°C using the same two-stage counterflow heat exchanger. The design basis for this is that (a) this design avoids auxiliary heating with a burner or electricity, and (b) a total of 28,000 BTU/hr is available to perform a total of 25,000 BTU/hr of preheat requirements. Only 14% of the available exhaust gas heat is used.

Table 7-1 presents the heat and mass balances. Figure 7-2 shows the two-stage heat exchanger concept (left side is heated by hot reformate; right side is heated by exhaust from engine).

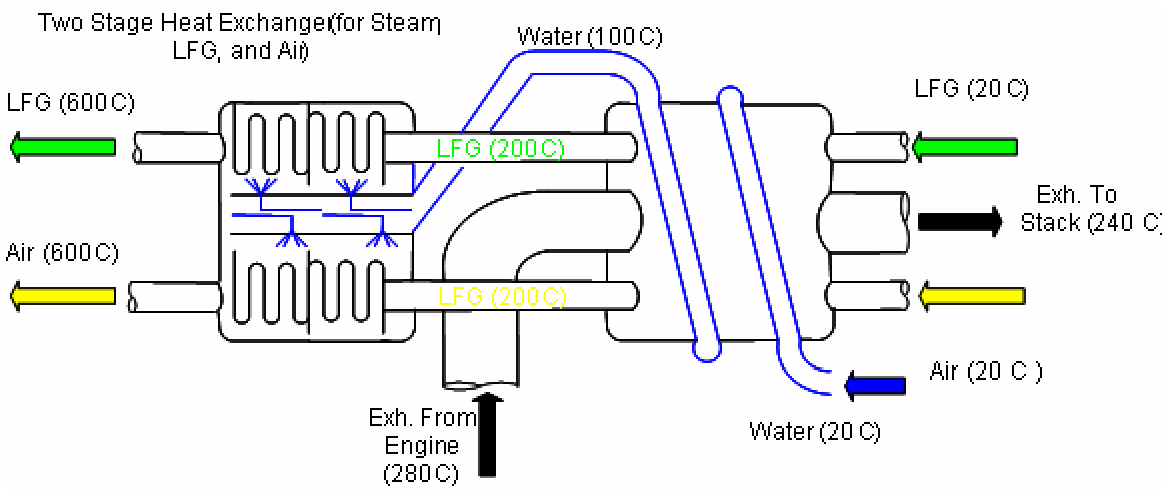


Figure 7-2. Two-Stage Heat Exchanger Concept

Table 7-1. Heat and Mass Balances

Heat and Mass Balance BioHALO 80kW System at 10% hydrogen by energy

Engine	engine power	80	kW					
	efficiency	34.1%						
	Heat rate	10000	BTU/kWh					
	BTU/hr input	800000	BTU/hr					
	CH4 flowrate norma	877.2	SCF/hr					
	LFG flowrate norma	1594.9	SCF/hr					
	Air flowrate lean	16736.8	SCF/hr	Assume 2X stoich air				
	Exhaust heat avail	140589.5	BTU/hr	post turbo	550F	288C	0.3 BTU/lbF	
	CH4 % bypass	84.9%						
Bypass	CH4 bypass	679405.0	BTU/hr	Density lb/SCF				
Reformer	CH4 flowrate	745.0	SCF/hr	0.041	30.5	CH4	CO2	N2
	CO2 flowrate	304.8	SCF/hr	0.112	34.1	55.0%	22.5%	22.5
	N2 flowrate	304.8	SCF/hr	0.072	21.9			
	LFG input	1354.5	SCF/hr		86.6	lb/hr		
Hydrogen	hydrogen %input	$\boxed{10.0\%}$						
	hydrogen input	80000	BTU/hr					
	hydrogen flow rate	290.9	SCF/hr	Input		output		
				O2/CH4	H20/CH4	CO/CH4	CO2/CH4	H2/CH4
Reformer	Equivalence ratio	3.0		0.667	1.5	0.5	0.5	2
Output	Temperature input	600	C	Density lb/SCF				
(ATR)	H2	290.9	SCF/hr	0.005	1.45	3.47	BTU/lbF	
	CO	66.1	SCF/hr	0.072	4.76			
	CO2	120.2	SCF/hr	0.112	13.46	0.3	BTU/lbF	
	H2O	171.9	SCF/hr	0.046	7.91			
	N2	386.6	SCF/hr	0.072	27.83			
	Total output flow	1035.7	SCF/hr		55.42	lb/hr		
	Reform heat availa	25229.1	BTU/hr	Need to cool 800C to 140C				
						31.17	lb/hr air	
Reformer	CH4	132.2	SCF/hr	0.041	lb/SCF	5.42	0.62	BTU/lbF
input	H2O	198.3	SCF/hr	0.046	lb/SCF	9.12		
	O2	88.2	SCF/hr	0.082	lb/SCF	7.23	0.26	BTU/lbF
	N2 in air	332.5	SCF/hr	0.072	lb/SCF	23.94	0.26	BTU/lbF
	N2 in LFG	54.1	SCF/hr	0.072	lb/SCF	3.89	0.26	BTU/lbF
	CO2 in LFG	54.1	SCF/hr	0.112	lb/SCF	6.06	0.26	BTU/lbF
	Total	859.4	SCF/hr		**Preheat w**	15.37	lb/hr LFG	
					Exhaust	**Hot reformate**		
Preheat	H20 to steam 600C	14188	BTU/hr		1500	12688	1555BTU/lb	
Required	Air preheat 600C	8462	BTU/hr		2538	5923	0.26 BTU/lbF	
	LFG preheat 600C	6216	BTU/hr		1865	4351	5.95 BTU/F	
	Total preheat req	**28865**	BTU/hr		**5903**	**22962**		
LFG	CH4	99.2	SCF/hr		4%	of avail exhaust heat		
Start up	CO2 In LFG	40.6	SCF/hr		91%	of avail reformate heat		
Burner	N2 in LFG	40.6	SCF/hr		**11.3%**	(energy penalty to preheat stea		
Input	N2 in air	747.8	SCF/hr					
	O2	198.3	SCF/hr					
	Total	1126.4	SCF/hr					
LFG	CO2	99.2	SCF/hr		Note: Add Air at 420 SCFH; add LFG at 24			
Burner	N2	788.3	SCF/hr		(During start up)			
Output	H2O	198.3	SCF/hr					
	Total	1085.9	SCF/hr					

Schematic drawings and Equipment List for BioHALO system

7.3.1. Schematic and P&IDs

The schematic for the BioHALO conceptual design is provided below as Figure 7-3.

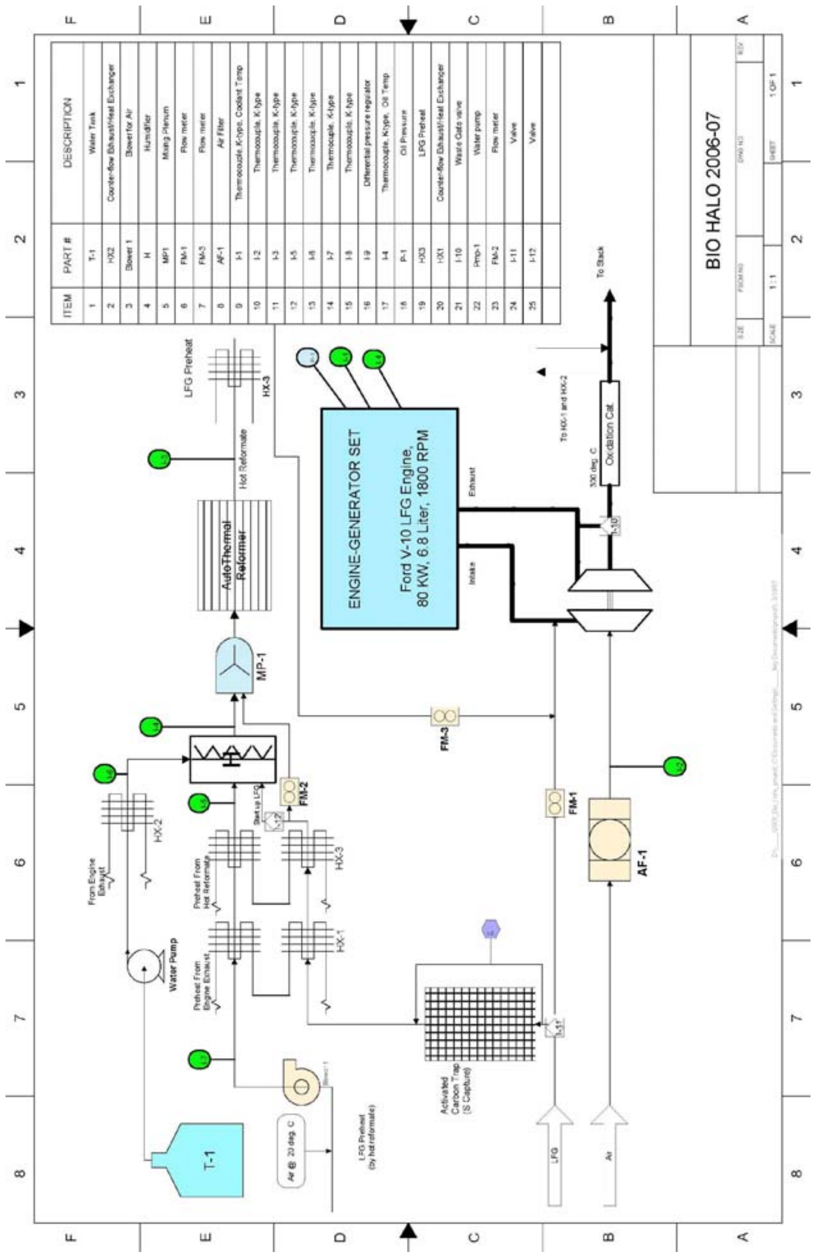


Figure 7-3. Schematic for the BioHALO Conceptual Design

7.3.2. *Equipment List*

The key components are listed in Table 7-2 below.

Table 7-2. Key Components

Component	Description; typical suppliers
Engine 50kW to 500kW	Ford, Gauscor, Deere, Waukesha landfill gas engine; turbocharged; high-energy spark for lean operation
Generator, Enclosure and Controls	LFG packager
Autothermal Reformer with subsystem sensors and controls	1000 SCFH input for 80 kW power; capable of 200% excess fuel operation; Unitel or equivalent
Special Two-Stage Heat exchanger	Gas-to-gas counterflow 20°C to 800°C
LFG Burner with air blower and flame sensors for start up	North American, other
In-line gas mixing plenum	LFG packager
Sulfur adsorption trap	Activated carbon or equivalent
Oxidation catalyst	Gas engine oxidation catalyst typical of industrial or off-road usage; Donaldson or equivalent.
Water pump and injector spray nozzles for steam	

Example of LFG Engine Gen Set: A typical 78 kW engine/ generator is the Hess Microgen generator set comprised of a Ford Power Products Model WSG-1068 V10 engine powering an induction generator with switchgear allowing interconnection to the grid. This set is designed to be installed at a landfill site and grid connected in parallel with the site electrical load. The engine was a 6.8 L natural gas fueled engine rated at 78 kW (105 hp) at 1,800 rpm using natural gas. A photograph of the side view of the LFG package with side door removed is provided in Figure 7-4. Table 7-3 gives the specifications.

Figure 7-4. Side View of Engine/Generator
Photo Credit: TIAX LLC

Table 7-3. Ford Power Products WSG-1068 Specifications

Specification	
Engine type	V10
Bore and Stroke, mm (in)	90.2 x 105.8 (3.55 x 4.17)
Displacement, L (CID)	6.8 (415)
Compression ratio	9:1
Net weight, kg (lb)	290 (640)
Ignition system	Coil on Plug
Rating on NG	78 kW (105 HP) @ 1800 RPM

7.4 Start-up and Operating Strategies for BioHALO System

A typical start up would proceed with the following steps:

1. The engine would be started and idled until the coolant temperature reached approximately 50°C.

2. The generator would then be connected up to the electrical grid, bringing the engine speed to 1800 rpm (at rated speed, no load).
3. The throttle would be opened, and fuel would automatically be added by the Motec system until a point of about 50% power was reached. The engine would be kept at this point until the oil and coolant temperatures reached the appropriate operating levels. During this time, the engine would be operated on 100% landfill gas.
4. The first step to starting hydrogen flow is to start the burner to preheat the reformer. About 10% LFG flow is turned on with stoichiometric air, and ignition is activated. The hot products heat the reformer catalyst.
5. When the reformer reaches 600°C, the engine power is raised to 100% to provide exhaust heat, and the LFG supply to the reformer is opened with the air flow corresponding to 200% excess fuel.
6. The water flow for steam is initiated to the heat exchangers, and when the steam pressure builds up, the reformer output gases are monitored for temperature and hydrogen content. The flows are adjusted to the correct mixture.
7. At this point, hydrogen would be added to the engine at the appropriate level by remixing reformate and LFG, and boost air is adjusted with the waste gate to lean out the mixture to 100% excess air. The desired operating point is now set.

Once the BioHALO system reaches steady-state, as evidenced by the emissions and the combustion stability, operation can commence at low NOx.

Auxiliary active thermal control (if needed): Clearly during the reformer start up (steps 4, 5, 6), the correct temperatures must be reached at the reformer inlet and exit, while sufficient cooling must be applied to keep fuel/air mixture at 40°C in the inlet manifold. Provision for auxiliary heating of the reformer is made by using a small gas-fired burner.

The burner can be used on unusually cold days or during temperature upsets to control the process.

7.5 Detailed Design of BioHALO System

7.5.1. Assembly Drawing of BioHALO Engine-Generator Reformer System

Figure 7-5 provides the assembly drawing of the BioHALO system based on a typical 75 kW engine/ generator, the Hess Microgen generator set, composed of a Ford Power Products Model WSG-1068 V10 engine powering an induction generator with switchgear allowing interconnection to the grid. This set is designed to be installed at a landfill site and grid connected in parallel with the site electrical load. The engine was a 6.8 L natural gas-fueled engine rated at 78 kW (105 hp) at 1,800 rpm using natural gas. A photograph of the side view of the LFG package with side door removed is provided in Figure 2.

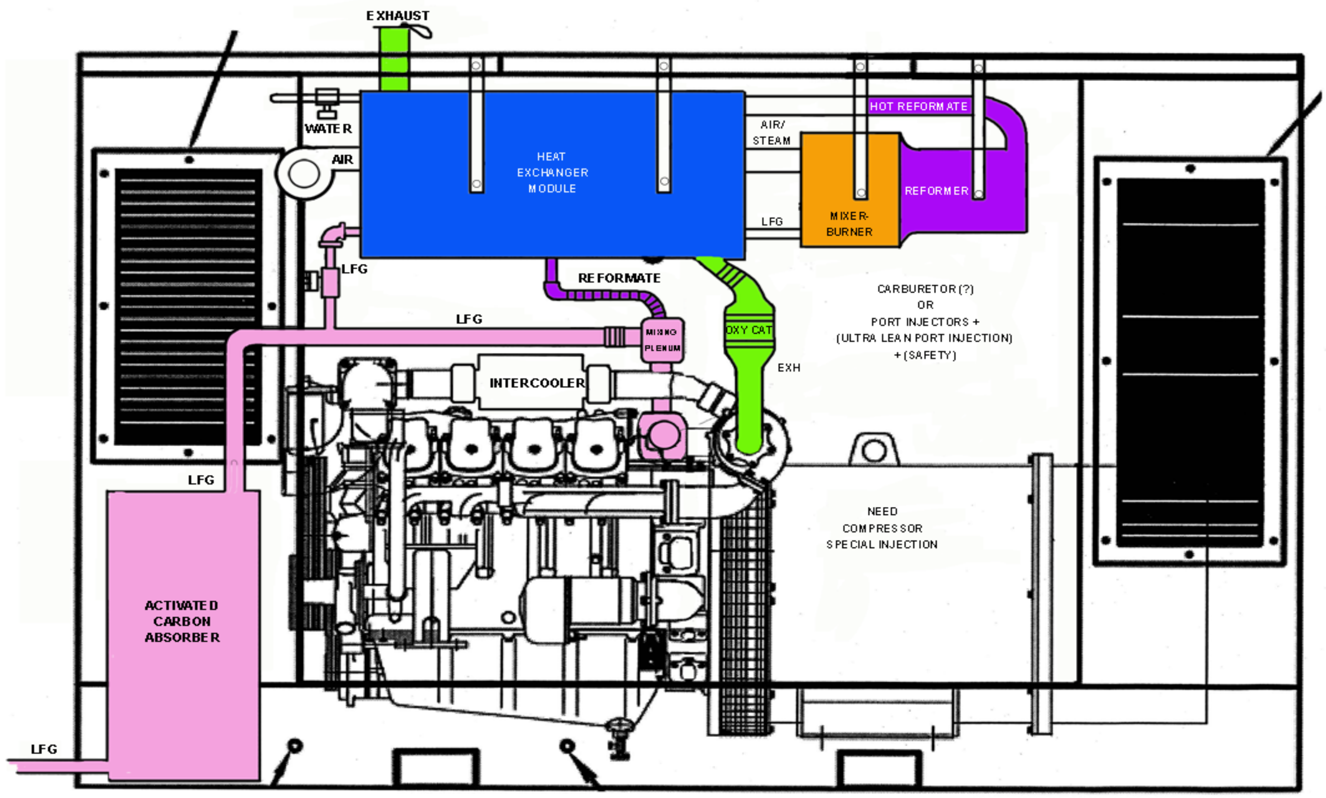


Figure 7-5. Assembly Drawing of BioHALO System

7.5.2. Illustration of Reformers (Commercially Available)

Figure 7-6 shows two commercially available reformers (Intelligent Energy and Aspen Products Group), both in the 5-10 kW size range suitable for BioHALO. The detailed drawings for these are proprietary. These two reformer products are stand-alone systems designed to produce ultra-high purity hydrogen for fuel cells from various fuels. The BioHALO application calls for a much simpler reformer resembling an automotive three-way catalyst, since (a) the raw reformate gas can be used directly by the engine without CO removal or other post-treatment, and (b) the feed gas is mainly methane and inerts (LFG). Therefore, either of these commercially available reformers could be simplified and adapted for the specified BioHALO autothermal process, which operates at equivalence ratio 3:1. Both illustrations include sulfur removal traps and extensive plumbing, not all of which may be necessary.

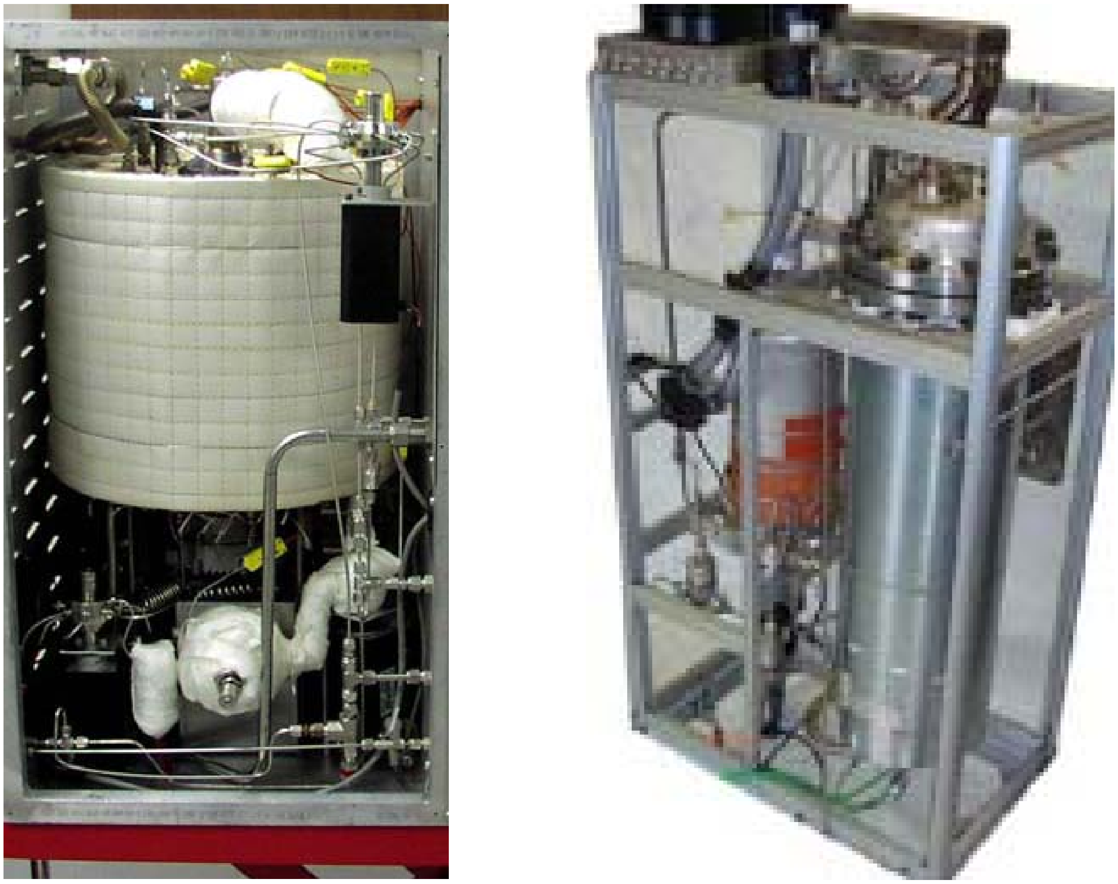


Figure 7-6. Commercially Available Reformers From Aspen Products Group (left) and Intelligent Energy (right)
Photo Credit: TIAX LLC

7.5.3. Heat Exchanger Subsystem Drawing

The hot reformate gas section of the heat exchanger module for an 80 kW BioHALO system is shown schematically below in. This unit is sized at 12 inches length by 16 square inches. Insulation must be added.

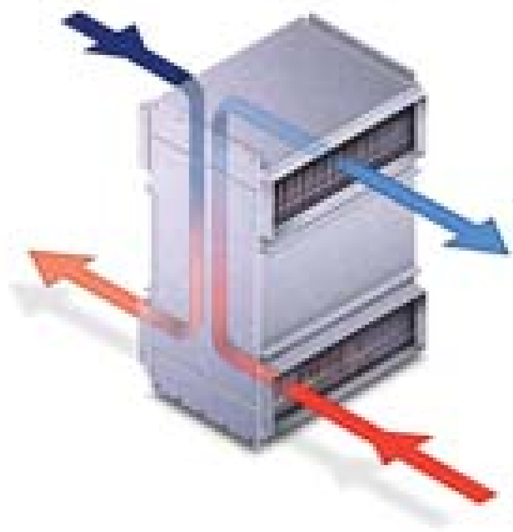


Figure 7-7. Heat Exchanger Module - Hot Section

The exhaust gas section of the heat exchanger module is sized at approximately 4 inches square by 18 inches long for both air preheat and LFG preheat. This section also vaporizes water into steam. The tube-in-shell cross-flow design is specified as shown below in Figure 7-8.

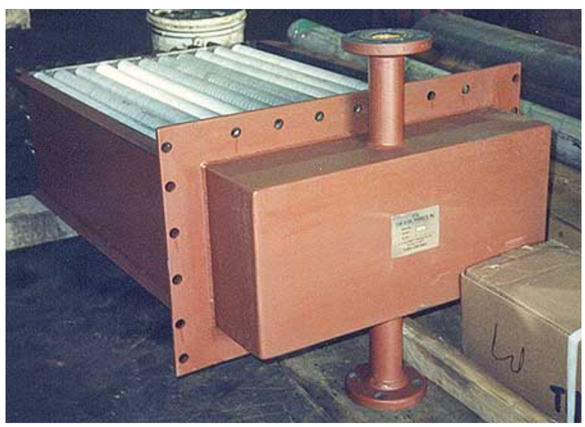


Figure 7-8. Heat Exchanger Module- Exhaust Section
Photo Credit: TIAX LLC

These two units are packaged together in the heat exchanger module 36 inches long and 12 inches wide, including insulation.

7.5.4. Engine Installation Drawing

The typical engine for an 80 kW BioHALO system is a Ford V-10 natural gas engine converted for landfill gas operation. Figure 7-9 shown below is the installation drawing for the LFG engine.

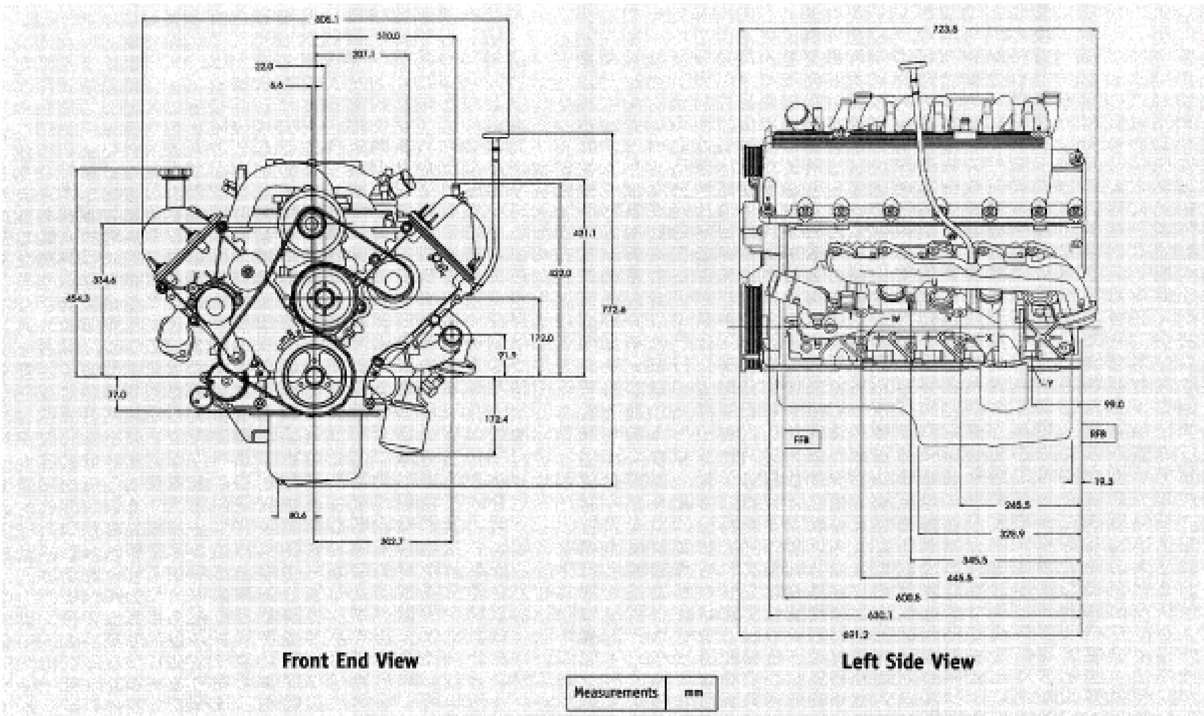


Figure 7-9. LFG Engine Converted From Ford V-10 Natural Gas Engine

7.5.5. Turbocharger Drawing

The typical turbocharger for an 80 kW BioHALO system is a Garrett model GT-32 shown below in Figure 7-10. The compressor map showing air flow and pressure ratio (and efficiency) is shown in Figure 7-11.

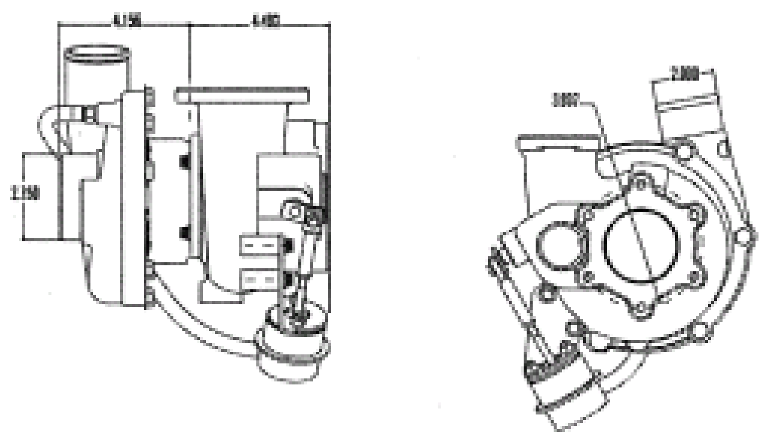


Figure 7-10. Turbocharger

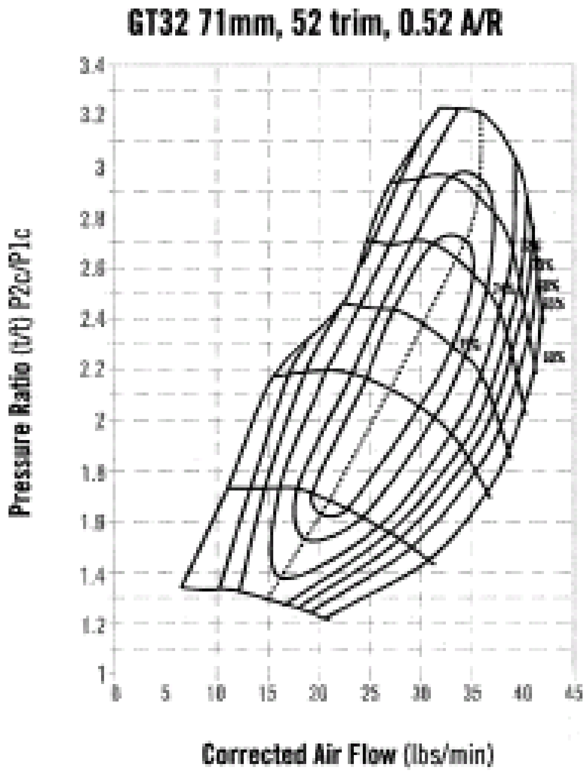


Figure 7-11. Compressor Map for Turbocharger for 80 kW BioHALO

7.5.6. Illustration of Oxidation Catalyst (Commercially Available)

In Figure 7-12 we show a commercially available oxidation catalyst (available from Miretek, Johnson-Matthey, and others) in the 50-100 kW engine size range suitable for BioHALO. The detailed drawings for this are proprietary.

Figure 7-12. Oxidation Catalyst

8.0 Equipment and Purchased Component Specifications

Based on the Conceptual Design reported as Task 2.4, the authors developed detailed specifications for the equipment and purchased components. The specifications are as follows:

8.1 Engine Generator Set

The generic LFG engine generator is assumed to be rated at 50 to 500 kW (80 kW is typical) with a heat rate of 10,000 BTU/kWh, which corresponds to 34.1% efficiency. The landfill gas is assumed to consist of 55% methane, 22.5% carbon dioxide, and 22.5% nitrogen or equivalent heating value. Table 8-1 lists the specifications.

- Target A/F ratio: 100% excess air.
- Required reformate mix ratio: 10% hydrogen to methane by heating value.
- Spark timing and type of ignition: High energy ignition 20° BTC.
- Intake manifold temperature: Maximum 60°C.

Table 8-1. Ford Power Products WSG-1068 Specifications

Specification	
Engine type	V10
Bore and Stroke, mm (in)	90.2 x 105.8 (3.55 x 4.17)
Displacement, L (CID)	6.8 (415)
Compression ratio	9:1
Net weight, kg (lb)	290 (640)
Ignition system	Coil on Plug
Rating on NG	78 kW (105 HP) @ 1800 RPM

8.2 Turbocharger and Other Engine Modifications for Lean Burn Operation on LFG

The standard engine must be modified to run at 100% excess air. This includes a turbocharger (Garrett GT32 or similar) to raise intake manifold pressure to 0.5 bar boost. Also the authors specify a high-energy spark system for lean operation. Finally, the air-fuel ratio must be the same for all cylinders within 1% to allow lean burn operation at low emissions. Therefore, a gas fuel port injection system is preferred for ultralean operation (the system must allow individual cylinder A/F ratio adjustment). If a carburetor is used, the intake manifold mixing must provide for the 1% maximum variation specified above.

8.3 Auto-Thermal Reformer

The auto-thermal reformer must be capable of operating at equivalence ratio 3:1 (200% excess fuel). This reformer can be designed around a low-cost catalyst similar to an automotive three-way catalyst and is slightly exothermic (adiabatic temperature rise of about 200°C between inlet and outlet). For catalyst light off, the inlet gases must be at 600°C.

- Required total flow rate: 900-1000 SCFH for 80kW.
- Acceptable reformate temperature range 700-900°C.
- Needed reformate hydrogen concentration 28% minimum.
- System pressure: Atmospheric.
- Duty cycle: 100% operation following engine load.
- Inlet levels of sulfur-containing gas below 10 ppB to avoid poisoning; requires activated carbon trap or similar.

8.4 Heat Exchanger Module

The BioHALO system requires a heat exchanger module to preheat both air and LFG going to the reformer to 600°C. Three gas inlet streams must be preheated to enter the reformer at 600°C (about 1100°F); the LFG itself, the water vapor (steam) required, and the air supply to the reformer. The module must be designed to extract heat from two sources of hot gas (sequentially):

In the first section, the heat exchanger module uses exhaust gas that exits the turbocharger intercooler at about 550°F (250°C). The exhaust gas section of the module (a) preheats water to 100°C before creating steam for the reformer, (b) partially preheats the air to the reformer up to 200°C, and (c) preheats the LFG slipsteam up to 200°C.

In the second section, hot reformate gas **is** run **through** a counter-flow heat exchanger to further preheat the LFG slipsteam from 200°C to 600°C**,** to further preheat air from 200°C to 600°C**,** and to vaporize water and raise the steam to 600°C**.**

The heat exchanger module is a custom design but uses conventional off-the-shelf materials as shown above in Figures 4 and 5.

8.5 Mixing Plenum, Air Blower, and Burner for Start-Up

For startup, a small burner is required to provide steam and to preheat the reformer catalyst to light-off temperature. About 100,000 BTU/hr LFG input rate or 10% of the engine fuel input is sufficient to start up the reformer system for an 80 kW engine generator. A mixing plenum tolerant of 600°C operation is provided because the three input steams to the reformer must be premixed (steam, air, and LFG). Also the air blower driving the air supply to the reformer is specified at 1000 SCF/hr and 8 inch water pressure.

8.6 Exhaust Oxidation Catalyst (Required to Meet Targets for CO and VOC Engine-Out Emissions)

The oxidation catalyst is a conventional off-the-shelf automotive or industrial unit with the following specifications:

- Engine exhaust temperature 280°C and flow rate 200 SCFH per kW rated power.
- Engine out exhaust THC 2000 ppm and CO concentration 700 ppm.
- Conversion efficiency 99% or better.
- Durability 4,000 hours (replace cartridge).
- Pressure drop 1 inch water maximum.

8.7 Controls

The control system is specified to follow engine load while controlling engine excess air and adjusting LFG slipstream flow rate to produce reformate flow at 10% hydrogen ratio by energy. The PID control loop holds the oxygen mole fraction at 10% plus or minus 0.2%. The system has the following additional specifications:

- Control algorithm type: based off H_2 concentration sensor and exhaust gas oxygen sensor.
- Control outputs and sensors and actuators are specified in Table 8-3 below.
- Response time (from 10% to 90% load) must be less than 30 engine cycles corresponding to 2 seconds at 1800 RPM.
- Reformer outlet temperature is set at maximum 850°C with shutoff of LFG slipstream if that temperature is exceeded for 5 seconds.
- If oil temperature exceeds 98°C, the LFG is shut off, and the engine is brought to idle for 5 minutes, then shut down and generate error message.
- If cooling water temperature exceeds 95°C same procedure.
- Emergency stops are provided to shut down LFG fuel valve and ignition system.
- System must be capable of data logging all key parameters for 200 hours at 5 minute intervals; with fast mode to capture shutdown record at 1 second intervals.
- System must have Ethernet protocol for remote access .

- If engine speed exceeds 1850 RPM, then shut off fuel valve.
- System must have capability for standard values input for PID control loop.

8.8 Bill of Materials

Table 8-2 provides a bill of materials of all critical purchased subsystems.

Table 8-2. Bill of Materials

Component	Description / Typical Suppliers	Estimated Cost, 80 kW system
Engine generator 50kW to 500kW, with enclosure and controls	LFG Packager such as Gauscor, Waukesha, Deutz or Caterpillar. Includes natural gas engine capable of operation on LFG. Cost estimate based on $540/kW without installation	$43,000
Turbocharger and other engine conversion components for lean burn LFG operation	Garrett model GT32 turbocharger or similar at $11 per kW. High-energy spark system for lean operation. Gas fuel port injection system preferred for ultralean operation (allows individual cylinder A/F ratio adjustment). IMPCO or Woodward carburetor valve is an option if uniform cylinder mix is feasible.	$900 $2000 $4000
Autothermal reformer with subsystem sensors and controls	1000 SCFH input for 80 kW power; capable of 200% excess fuel operation; Intelligent Energy, Aspen or equivalent	$8000
Special two-stage heat exchanger	Gas-to-gas counterflow 20°C to 800°C according to drawing in this report	$2000
LFG Burner 100,000 BTU/hr with 1000 SCFH air blower at 8 in. wc and mixing plenum	Coen, North American, or equivalent. Blower Mixing Plenum, 600°C tolerant	$1000 $500 $500
Sulfur and siloxane adsorption trap	Activated carbon or equivalent	$2000
Oxidation catalyst	Gas engine oxidation catalyst typical of industrial or off-road usage; suppliers include Johnson-Matthey, Donaldson or equivalent.	$500
Water pump and injector spray nozzles for steam		$200
Solenoid valves (2)	Asco or equivalent	$400
Ethernet connection and data logging		$500
Piping and fittings		$100

8.9 Description of Start-Up and Operating Controls Functions

8.9.1. Start-Up Control Sequence

The standard controls (sensors, actuators, and control logic) shown in the P&ID schematic (see below) will be used to replicate electronically the following steps for start up and control:

1. The engine would be started (relay to starter solenoid opened until RPM reaches 300) and idled until the coolant temperature reached approximately 50°C.
2. The generator would then be connected to the electrical grid (contactor closed), bringing the engine speed to 1800 rpm (at rated speed, no load).
3. The throttle would be opened, and fuel would automatically be added by the IMPCO fuel valve actuator until a point of about 50% power was reached. The engine would be kept at this point until the oil and coolant temperatures reached the appropriate operating levels. During this time, the engine would be operated on 100% landfill gas.
4. The first step to starting hydrogen flow is to start the burner to preheat the reformer. (The LFG reformate valve is opened, and the blower relay activated). About 10% LFG flow is turned on with stoichiometric air, and ignition is activated. The hot products heat the reformer catalyst.
5. When the reformer reaches 600°C, the engine power is raised to 100% (throttle opened to "wide open") to provide exhaust heat and the LFG supply to the reformer is opened and the air flow corresponding to 200% excess fuel.
6. The water flow for steam is initiated (water pump relay activated) to the heat exchangers, and when the steam pressure builds up, the reformer output gases are monitored for temperature and hydrogen content. The flows are adjusted using the LFG reformate control valve to the correct mixture.
7. At this point, hydrogen would be added to the engine at the appropriate level, and the waste gate valve at the turbocharger is adjusted to initiate boost and lean out the mixture to 100% excess air. The desired operating point is now set.

Table 8-3 provides a list of the critical sensors, actuators and controls needed for BioHALO. These sensors are shown in the P&ID schematic in Figure 10.

Table 8-3. BioHALO Control System Specifications

Sensor or Component	Input / Output Mode	Comments
Hall Effect Camshaft Sensor	TTL input	Reference signal for engine control, provides engine speed
Hall Effect Crankshaft Sensor	TTL input	Timing signal for engine control
Universal Exhaust Gas Oxygen Sensor (UEGO)	Analog voltage input	Allows for closed loop fuel control
Coils (x 10)	TTL output	Spark signal to coil igniter
Line Voltage (x3)	Analog voltage input	Monitors electrical grid connection
Line Current (x 3)	Analog voltage input	Monitors electrical grid connection
Line Phase (x 3)	Analog voltage input	Monitors electrical grid connection
Generator Power	Analog voltage input	Monitors electrical grid connection
Emergency Stop	Digital output	Shuts down system
LFG Supply Solenoid	Digital output	Fuel Supply Valve
Generator T/C	Analog voltage input	Monitors Generator temperature

Sensor or Component	Input / Output Mode	Comments
Waste Gate Actuator	PWM signal	Adjusts turbocharger Wastegate
LFG Flowmeter and Valve	0-10 V Analog voltage input and PWM	Monitor and adjust LFG flow rate
Reformate LFG Flowmeter	0-10 V analog voltage input	Monitor LFG flow to reformer
Activated Carbon Trap Differential Pressure Sensor	0-10 V analog voltage input	Monitors clogging of LFG filter
Fuel Valve (x 10)	TTL output	Send signal to fuel valve
Manifold Absolute Pressure Sensor	0-5 V analog voltage input	Boost pressure input for engine control
Reformer T/c	0-5 V analog voltage input	Temperature monitoring o reformer
H_2 Sensor	0-5 V analog voltage input	Output monitoring of reformer
Oil Pressure Sensor	0-5 V Analog voltage input	Monitors engine oil pressure
Oil Temperature Sensor	RRTD input	Monitors engine coolant pressure
Water Tank Level Sensor	0-10 V analog voltage input	Monitors level of water
System T/C (x 6)	Analog voltage input	Process flow temperature monitoring
Blower Power	TTL output	Activates relay to turn blower on/of
Water Pump Power	TTL output	Activates relay to turn water pump on/off
Coolant Temperature Sensor	0-5 V analog voltage input	Monitors engine coolant temperature
Throttle Position sensor	PWM signal	Position of engine throttle

8.10

8.11 Mechanical, Piping, and Electrical Connections

The drawing packages for the mechanical, piping, and electrical grid connections are provided below.

MARATHON ELECTRIC®

A Subsidiary of Regal-Beloit Corporation

CERTIFICATION DATA SHEET

CUSTOMER: Hess

CUSTOMER P.O.

MODEL NO: 365TTDS4641

MEMC ORDER NO:

CONN. DIAGRAM:

ADAPTION #:

OUTLINE:

WK^2: 15.5 lb-ft^2

WINDING: T3654166

TYPICAL MACHINE DATA

KW	SYNC RPM	FL RPM	FRAME	ENCLOS	OVERSPEED RPM	HIGH VOLT RESISTANCE
80	1800	1830	365	ODP	2250	0.105 ohm

PH	HZ	VOLTS	FL AMPS	Magnetizing (NL) AMPS @ Hi Volts	DUTY	INSUL	S.F.	AMB (°C)
3	60	208-240 / 416-480	270-232 / 135-116	27 - 33	CONT	F	1.0	40

NOMINAL EFF (%)			POWER FACTOR (%)			TQ @ FULL VOLTS (LB-FT)		
FL	3/4 LD	1/2 LD	FL	3/4 LD	1/2 LD	FL	LR	BREAKAWAY
92.4	93.0	93.6	83.0	81.5	76.5	333	540	1000

EQUIVALENT CIRCUIT REACTANCES (PER UNIT) Zref = 2.662 ohms

Stator Resistance R1	Rotor Resistance R2	Stator Reactance X1	Rotor Reactance X2	Magnetizing Reactance Xm	Transient Reactance X'd	Sub-Transient (short ckt) Reactance X"d
0.030	.0155	0.110	.142	3.039	0.250	0.140

FAULT CURRENT, TIME CONSTANTS (SECOND)

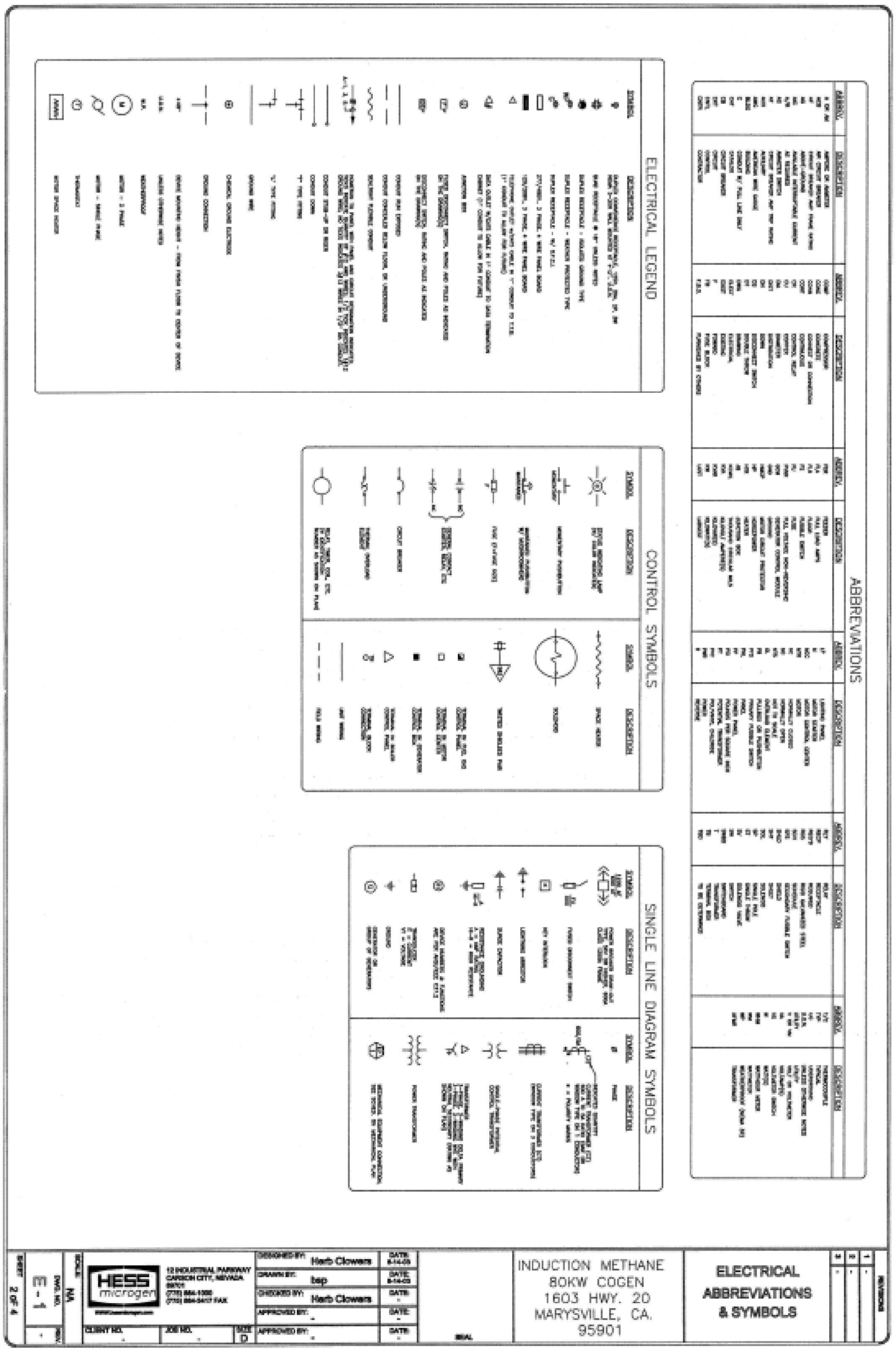
Fault Current AMPS	SHORT CKT T'd (sec)	OPEN CKT T'do (sec)
650	0.545	.022

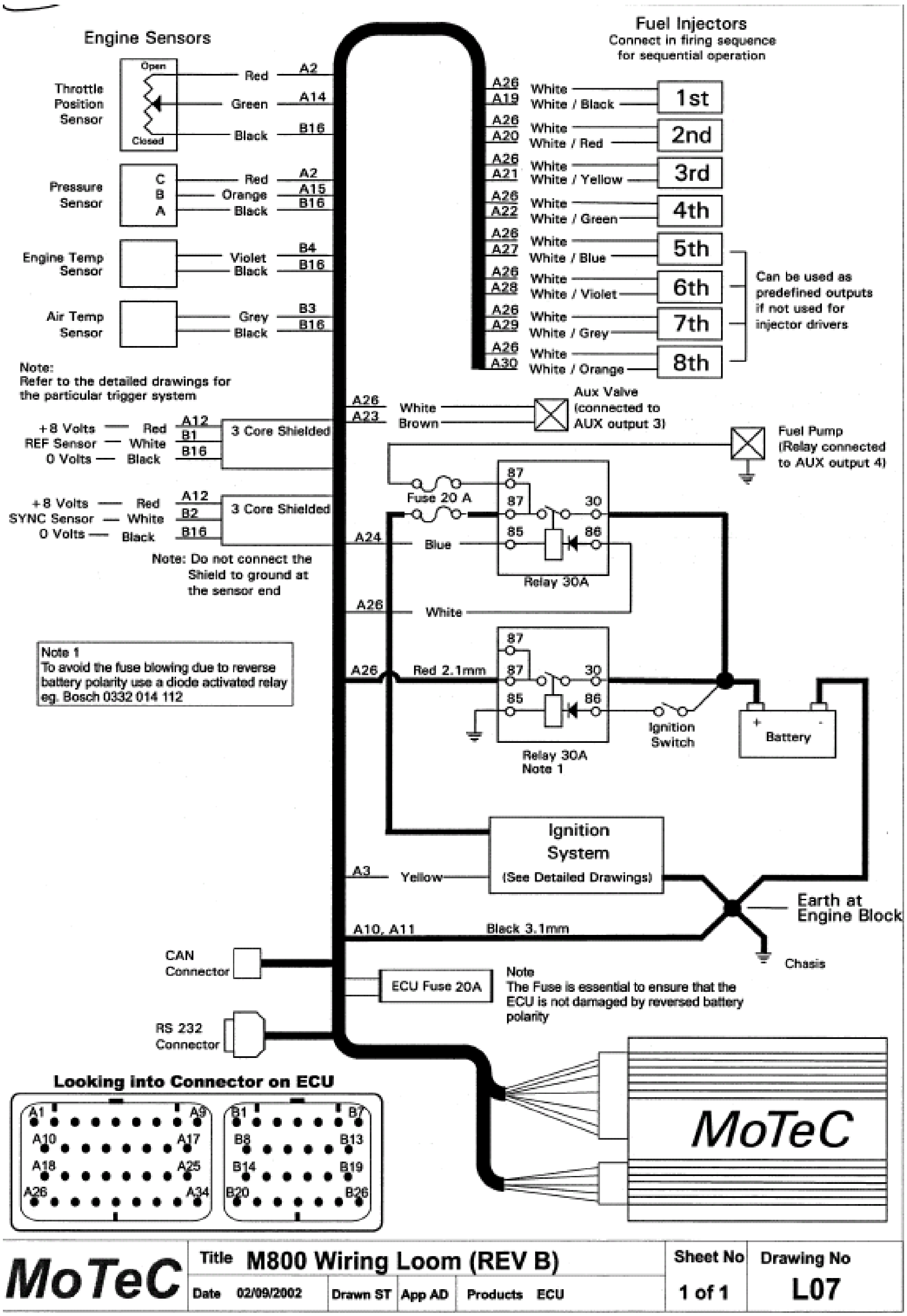
SUPPLEMENTAL INFORMATION

1) 26 KVAR's at No Load; 53.5 KVAR's at 80 KW Load

CERTIFIED BY: Earl Babbitts

DATE: 21-AUGUST-03


ELECTRICAL LEGEND
CONTROL SYMBOLS
SINGLE LINE DIAGRAM SYMBOLS
ABBREVIATIONS
INDUCTION METHANE
80KW COGEN
1603 HWY. 20
MARYSVILLE, CA.
95901
ELECTRICAL
ABBREVIATIONS
& SYMBOLS
HESS
microgen
Herb Clowers
bsp
Herb Clowers
E-1
2 OF 4



Engine Sensors
Throttle Position Sensor
Open
Closed
Red A2
Green A14
Black B16
Pressure Sensor
C B A
Red A2
Orange A15
Black B16
Engine Temp Sensor
Violet B4
Black B16
Air Temp Sensor
Grey B3
Black B16
Note:
Refer to the detailed drawings for the particular trigger system
+8 Volts Red A12
REF Sensor White B1
0 Volts Black B16
3 Core Shielded
+8 Volts Red A12
SYNC Sensor White B2
0 Volts Black B16
3 Core Shielded
Note: Do not connect the Shield to ground at the sensor end
Note 1
To avoid the fuse blowing due to reverse battery polarity use a diode activated relay eg. Bosch 0332 014 112
Fuel Injectors
Connect in firing sequence for sequential operation
A26 A19 White White / Black 1st
A26 A20 White White / Red 2nd
A26 A21 White White / Yellow 3rd
A26 A22 White White / Green 4th
A26 A27 White White / Blue 5th
A26 A28 White White / Violet 6th
A26 A29 White White / Grey 7th
A26 A30 White White / Orange 8th
Can be used as predefined outputs if not used for injector drivers
A26 White
A23 Brown
Aux Valve (connected to AUX output 3)
Fuel Pump (Relay connected to AUX output 4)
Fuse 20 A
87 87 30 85 86
A24 Blue
Relay 30A
A26 White
87 87 30 85 86
A26 Red 2.1mm
Relay 30A Note 1
Ignition Switch
Battery
Ignition System (See Detailed Drawings)
A3 Yellow
Earth at Engine Block
A10, A11 Black 3.1mm
Chasis
CAN Connector
ECU Fuse 20A
Note
The Fuse is essential to ensure that the ECU is not damaged by reversed battery polarity
RS 232 Connector
MoTeC
Looking into Connector on ECU
A1 A9 A10 A17 A18 A25 A26 A34
B1 B7 B8 B13 B14 B19 B20 B26
MoTeC
Title M800 Wiring Loom (REV B)
Date 02/09/2002
Drawn ST
App AD
Products ECU
Sheet No 1 of 1
Drawing No L07

M-3410 Typical Connection Diagram

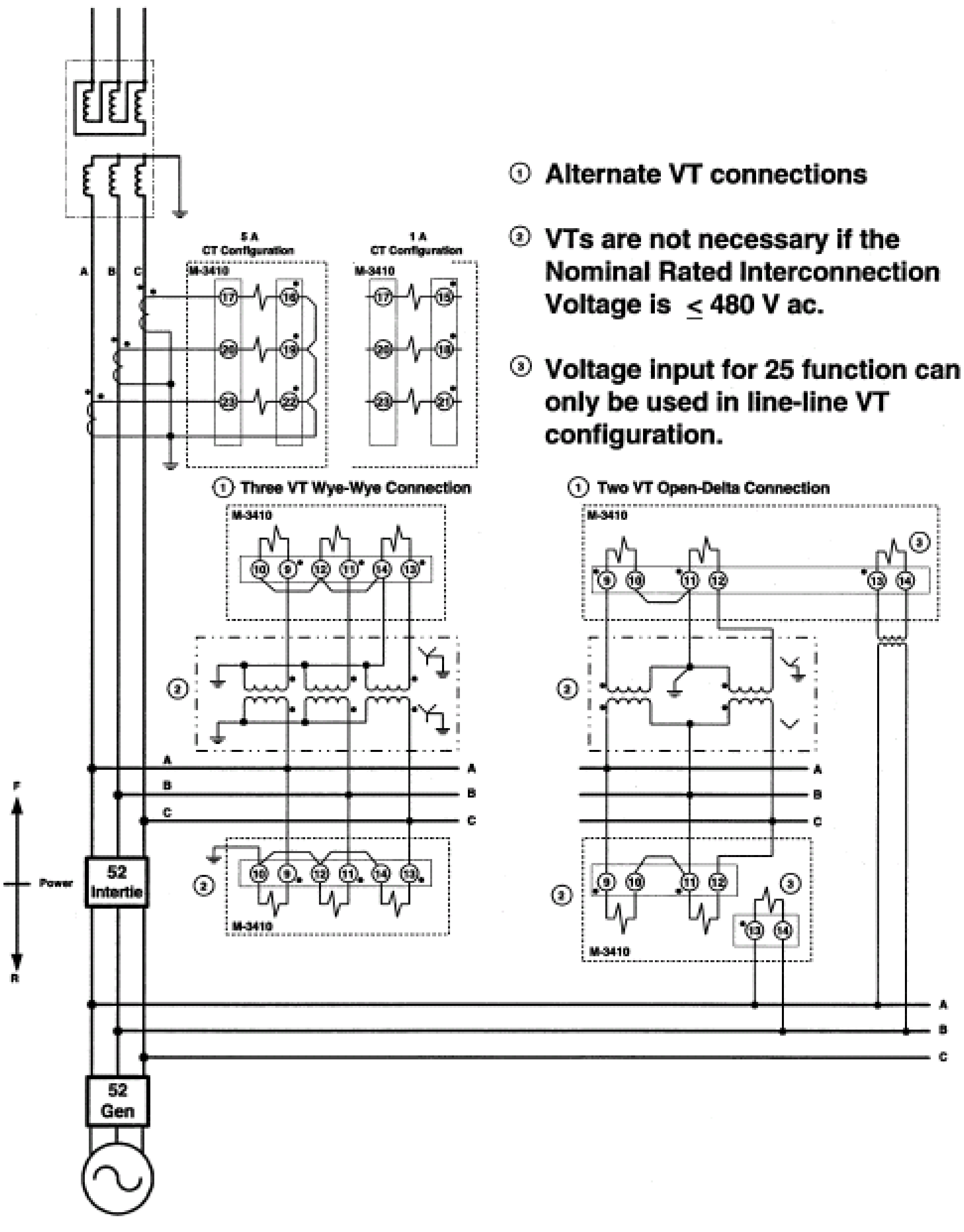


Figure 6 Typical Three-Line Diagram–Intertie Protection

External Connections

M-3410 external connection points are illustrated in Figure 1, External Connections, below.

Specification is subject to change without notice.

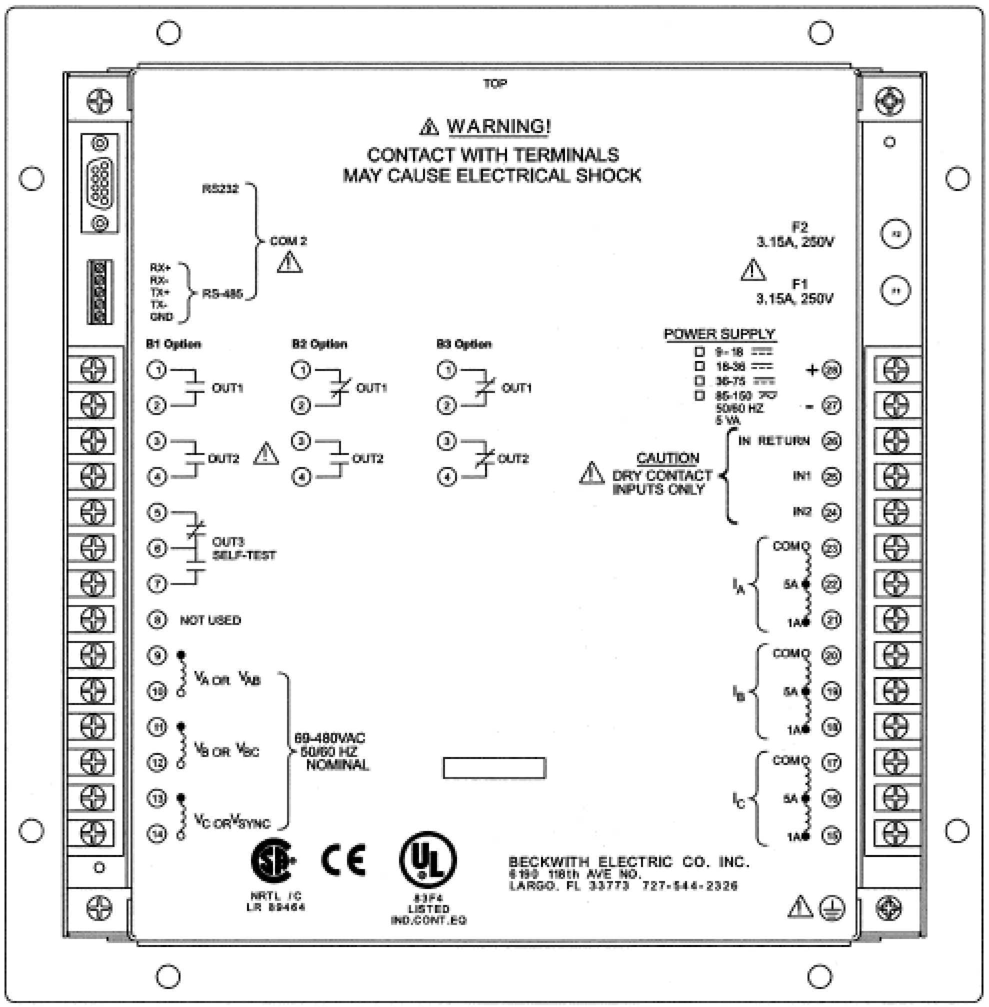


Figure 1 External Connections

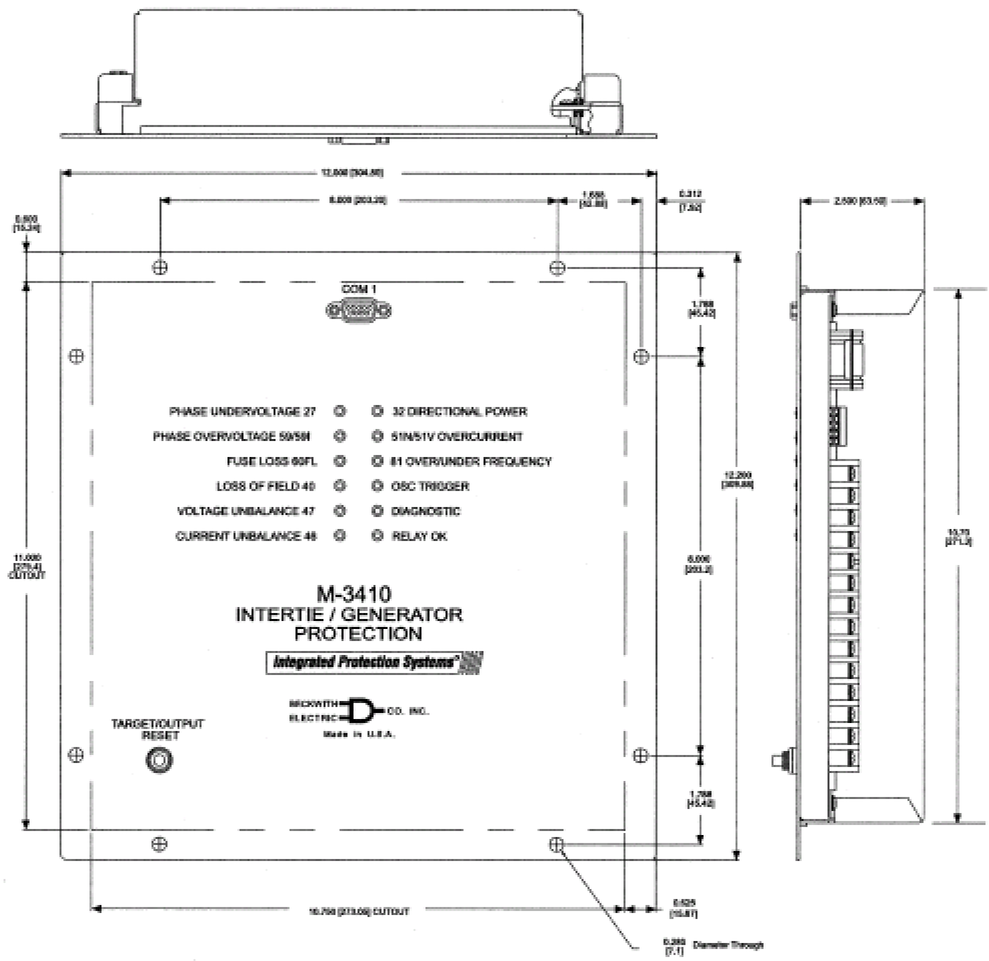


Figure 2 Mounting Dimensions

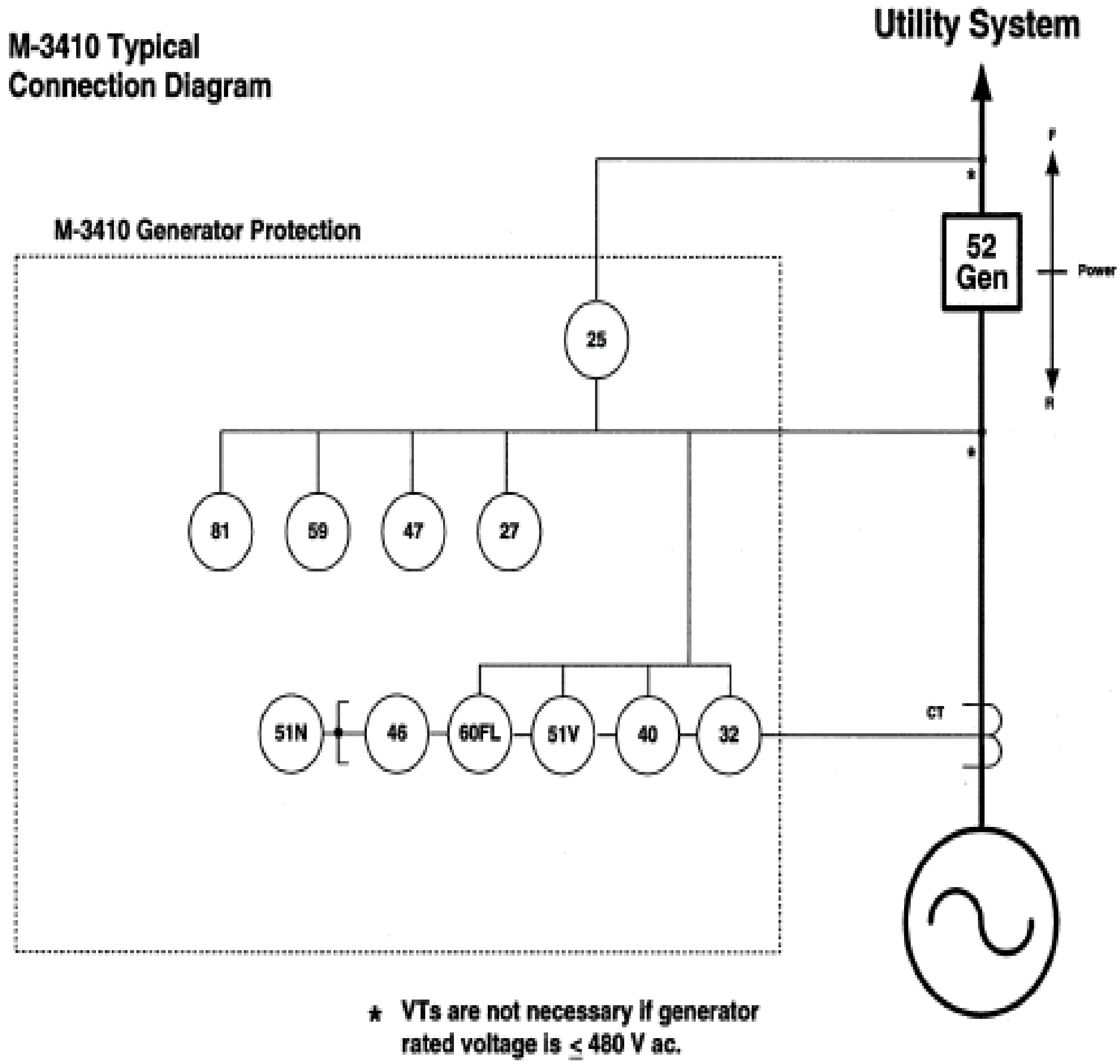


Figure 3 Typical One-Line Diagram–Generator Protection

M-3410 Typical Connection Diagram

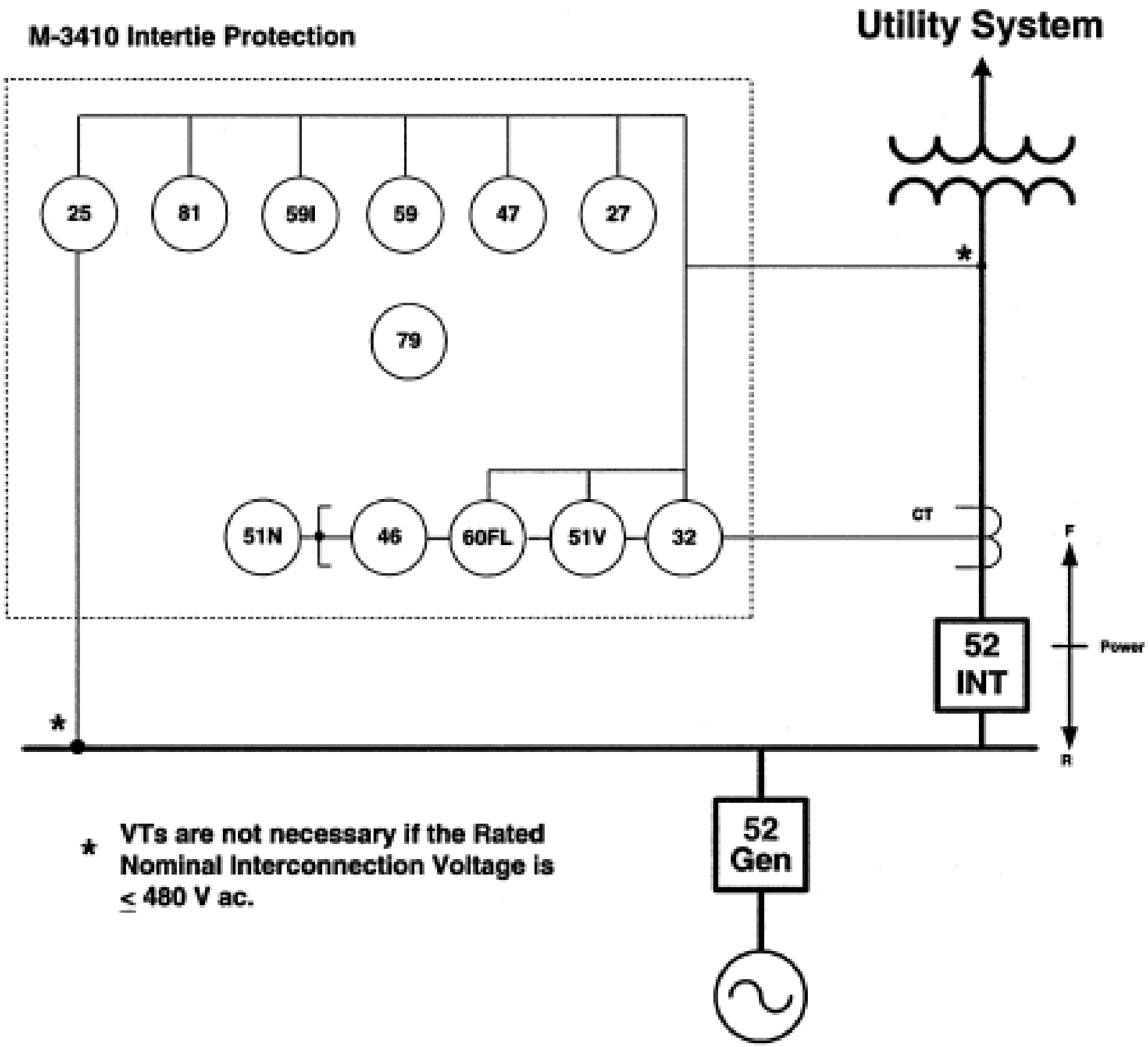
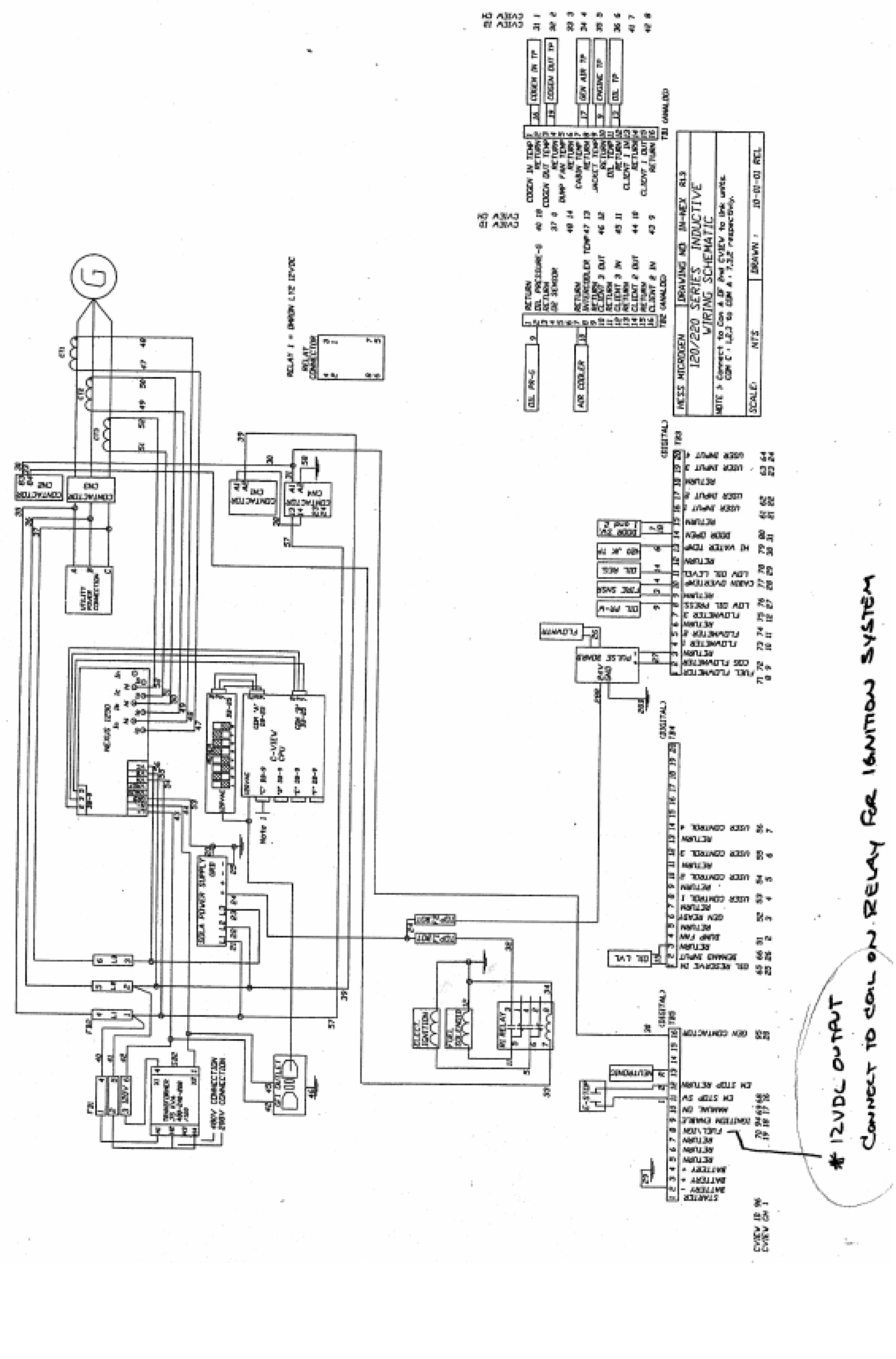


Figure 4 Typical One-Line Diagram–Intertie Protection


HESS MICROGEN
120/220 SERIES INDUCTIVE
WIRING SCHEMATIC
* 12VDC OUTPUT
CONNECT TO COIL ON RELAY FOR IGNITION SYSTEM

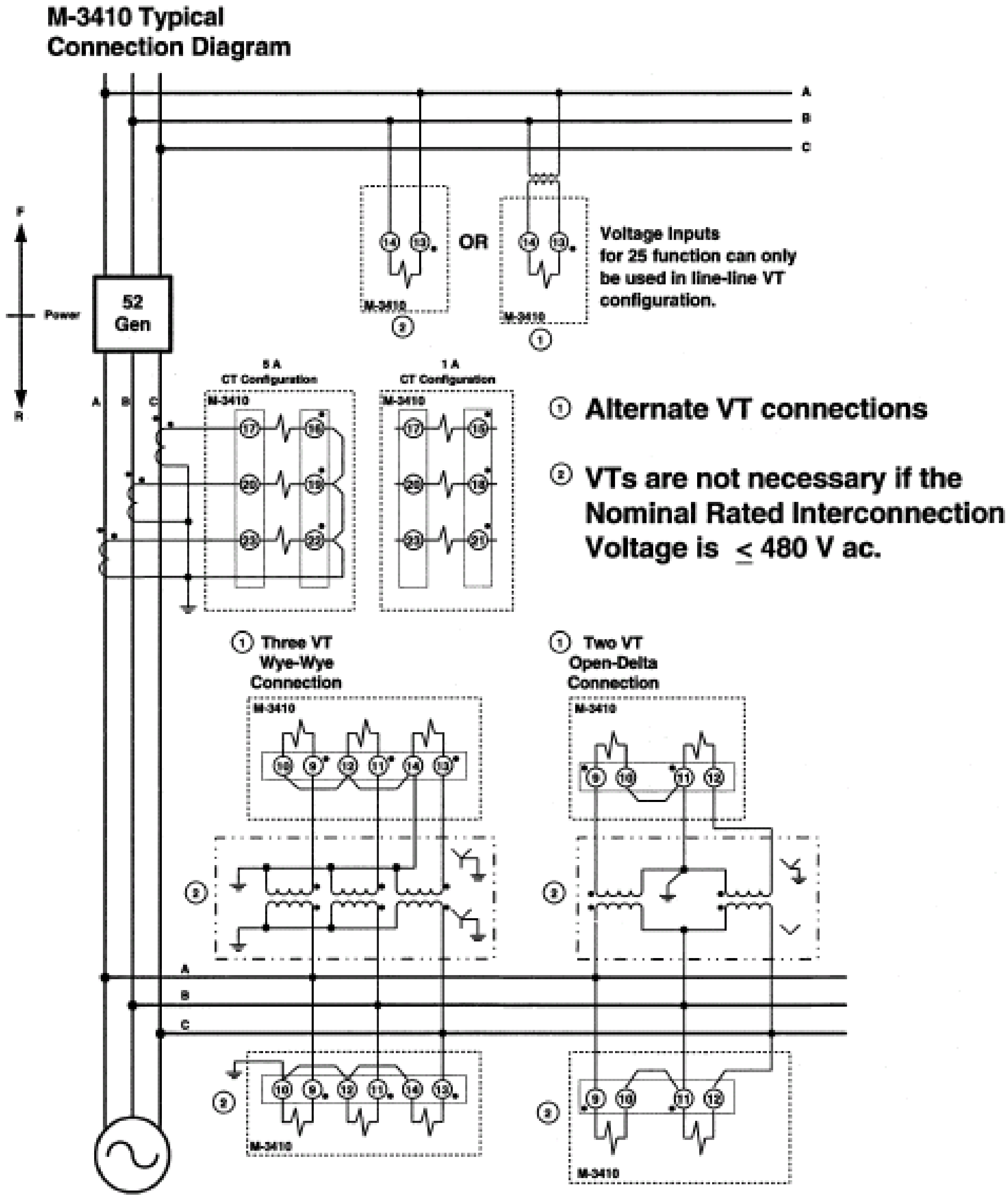
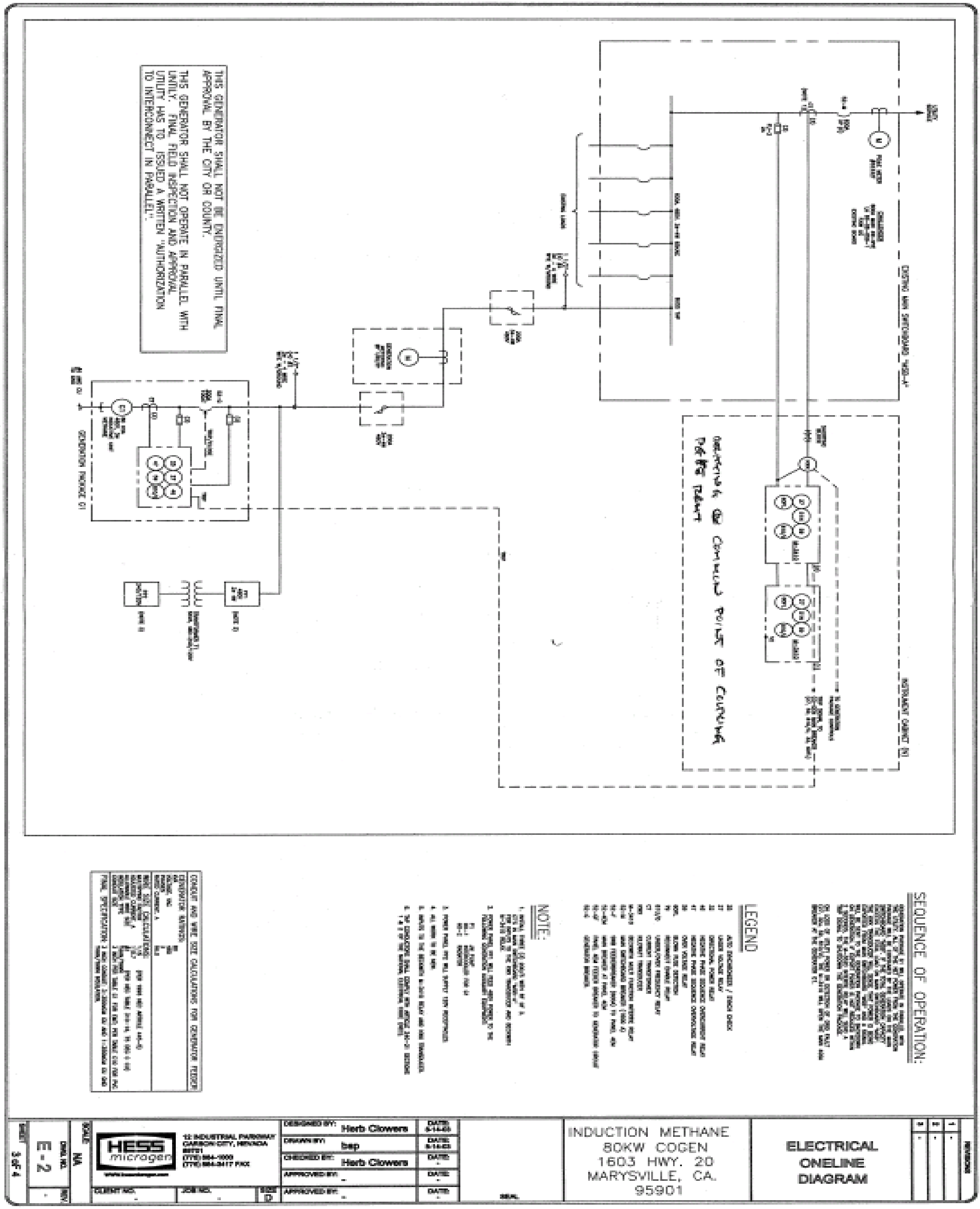
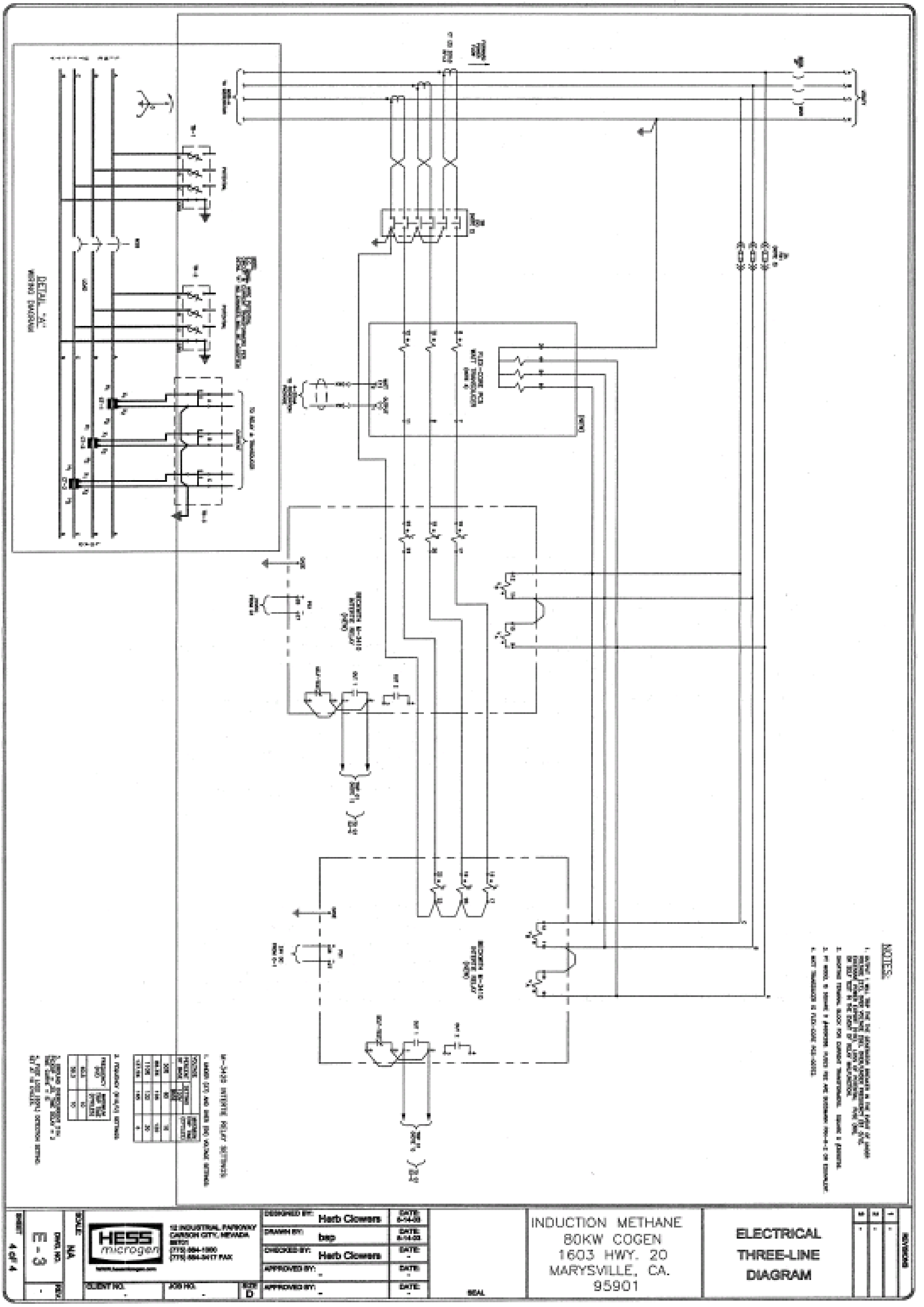


Figure 5 Typical Three-Line Diagram–Generator Protection


INDUCTION METHANE
80KW COGEN
1603 HWY. 20
MARYSVILLE, CA.
95901
ELECTRICAL
ONELINE
DIAGRAM
DESIGNED BY: Herb Clowers
DRAWN BY: bep
CHECKED BY: Herb Clowers
APPROVED BY:
HESS
microgen
E-2
SEQUENCE OF OPERATION:
LEGEND
NOTE:
THIS GENERATOR SHALL NOT BE ENERGIZED UNTIL FINAL
APPROVAL BY THE CITY OR COUNTY.
THIS GENERATOR SHALL NOT OPERATE IN PARALLEL WITH
UTILITY. FINAL FIELD INSPECTION AND APPROVAL
UTILITY HAS TO ISSUED A WRITTEN "AUTHORIZATION
TO INTERCONNECT IN PARALLEL".


INDUCTION METHANE
80KW COGEN
1603 HWY. 20
MARYSVILLE, CA.
95901
ELECTRICAL
THREE-LINE
DIAGRAM
NOTES:
DETAIL "A"
WIRING DIAGRAM
HESS
microgen
12 INDUSTRIAL PARKWAY
CARSON CITY, NEVADA
89701
(775) 884-1950
(775) 884-0417 FAX
DESIGNED BY:
Herb Clowers
DRAWN BY:
bsp
CHECKED BY:
Herb Clowers
APPROVED BY:
DATE:
SEAL
SCALE
N/A
DWG. NO.
E - 3
SHEET
4 of 4
REV.
CLIENT NO.
JOB NO.
SIZE
D
REVISIONS

GENERAL ELECTRICAL NOTES:

1. WORK INCLUDES INSTALLATION OF ALL ELECTRICAL SYSTEMS COMPLETE AND OPERATIONAL TO THE SATISFACTION OF THE OWNER AS LIMITED BY THE INTENT OF THE CONTRACT DOCUMENTS.
2. FURNISH ALL LABOR, MATERIALS, TOOLS, ACCESSORIES, ETC. REQUIRED FOR A COMPLETE WORKING ELECTRICAL SYSTEM.
3. OBTAIN ALL NECESSARY PERMITS.
4. ALL ELECTRICAL WORK SHALL COMPLY WITH ALL APPLICABLE STATE, COUNTY AND LOCAL CODES AND ORDINANCES, AS WELL AS ALL CURRENT STANDARDS, CODES AND PRACTICES AS REQUIRED BY NEC, NEMA, ANSI, NFPA, UBC, UL, IEEE AND UTILITY COMPANY STANDARDS.
5. VISIT THE JOB SITE AND VERIFY ALL EXISTING CONDITIONS AND THE EXTENT OF REMOVAL, RELOCATION, RECONNECTION AND/OR NEW WORK PRIOR TO BIDDING. BID SUBMISSION SHALL BE CONSIDERED AS EVIDENCE OF SITE INSPECTION AND RESOLUTION OF ALL DISCREPANCIES AND QUESTIONS. NO EXTRA PAYMENT WILL BE AUTHORIZED FOR WORK MADE NECESSARY BY FAILURE TO COMPLY.
6. APPEARANCE AND WORKMANSHIP SHALL BE OF THE HIGHEST STANDARDS OF QUALITY ANALOGOUS TO THE JOB.
7. ELECTRICAL CONTRACTOR SHALL GUARANTEE THE ELECTRICAL WORK TO BE FREE FROM DEFECTS IN MATERIALS AND WORKMANSHIP FOR A PERIOD OF ONE YEAR FROM DATE OF FINAL ACCEPTANCE. LIGHTING LAMPS SHALL BE EXEMPT FROM THIS REQUIREMENT BUT SHALL BE NEW AND IN PERFECT WORKING ORDER AT THE TIME OF FINAL ACCEPTANCE.
8. ELECTRICAL CONTRACTOR SHALL COORDINATE HIS WORK WITH THE PLANS, SPECIFICATIONS AND WORK OF ALL OTHER TRADES. NO EXTRA PAYMENT WILL BE MADE FOR WORK OR MATERIALS RESULTING FROM LACK OF COORDINATION.
9. VERIFY THE EXACT LOCATION AND ELEVATION OF ALL ELECTRICAL EQUIPMENT PRIOR TO ROUGH-IN. FINAL CONNECTIONS OF EQUIPMENT SHALL BE PER MANUFACTURERS APPROVED WIRING DIAGRAMS, DETAILS AND INSTRUCTIONS. THE ELECTRICAL CONTRACTOR SHALL PROVIDE MATERIALS AND EQUIPMENT COMPATIBLE WITH EQUIPMENT ACTUALLY SUPPLIED.
10. ELECTRICAL CONTRACTOR SHALL PROVIDE A NEAT AND COMPLETE SET OF "AS-BUILT" DRAWINGS WITHIN 30 DAYS OF FINAL ACCEPTANCE OF HIS WORK.
11. ORDER AND/OR RELEASE ORDERED MATERIALS PROMPTLY AFTER SUBMITTAL APPROVAL. NO SUBSTITUTIONS OR ALTERNATE METHODS OF INSTALLATION WILL BE ACCEPTED FOR FAILURE TO ORDER MATERIALS IN A TIMELY FASHION.
12. OBTAIN WRITTEN APPROVAL FROM THIS ENGINEER OF ALL SHOP DRAWINGS AND MANUFACTURERS DATA FOR SWITCH GEAR, LIGHTING FIXTURES, WIRING DEVICES, ETC. BEFORE RELEASING ORDERED MATERIALS. SUBMITTAL DATA SHALL INDICATE THAT THE CONTRACTOR HAS REVIEWED THE MANUFACTURES DATA AND THAT THE PROPOSED EQUIPMENT WILL MEET THE PHYSICAL CONSTRAINTS AT THE JOBSITE. ANY SUBSTITUTIONS SHALL BE OF EQUIVALENT OR BETTER QUALITY THAN THE SPECIFIED COMPONENTS.
13. SHORT CIRCUIT INTERRUPTING RATINGS AS INDICATED ON THESE PLANS REFER TO BOTH BUSS BAR BRACING AND CIRCUIT BREAKER WITHSTAND LEVELS.
14. INDOOR WIRING SHALL BE ACCOMPLISHED USING E.M.T. CONDUIT WITH STEEL & INSULATED THROAT FITTINGS. SET SCREW FITTINGS ARE PROHIBITED AND WILL NOT BE APPROVED. CONDUCTOR SHALL BE TYPE THHN/THWN COPPER. TYPE MC, AND TYPE AC CABLE AND TYPE E.N.T. CONDUIT IS NOT ALLOWED
15. CONDUIT/CONDUCTOR RUNS SHOWN ARE DIAGRAMMATICAL ONLY. THE BEST FINAL CONDUIT ROUTING SHALL BE AS DETERMINED BY THE ELECTRICAL CONTRACTOR AT TIME OF CONSTRUCTION.
16. ALL WIRE SHALL BE STRANDED COPPER.
17. CONDUIT SIZES CALLED OUT ON THE DRAWINGS ARE NOT NECESSARILY BASED ON THE MINIMUM SIZE ALLOWED BY NFPA 70 AND MAY BE PURPOSELY OVERSIZED FOR FUTURE CONDUCTORS OR TO AVOID EXCESS CONDUIT HEATING. CONDUIT SIZES NOT CALLED OUT ON DRAWINGS SHALL BE SIZED PER NFPA 70 BY THE CONTRACTOR, BASED ON THE ACTUAL NUMBER OF CONDUCTORS TO BE INSTALLED. IN NO CASE SHALL CONDUIT SIZES BE SMALLER THAN IS REQUIRED BY NFPA 70.
18. ALL CONDUIT SHALL BE EXPOSED ON CONCRETE WALLS AND CONCEALED FOR SHEET ROCK WALLS. THE MINIMUM SIZE IS 3/4 INCH. EMT MAY BE USED FOR INDOOR CONCEALED CONDUIT RUNS 2" OR SMALLER. EXPOSED CONDUIT, CONDUIT SUBJECT TO MOISTURE, OR CONDUIT LARGER THAN 2" SHALL BE RIGID GALVANIZED STEEL. CONDUIT IN CAST-IN-PLACE CONCRETE OR UNDER SLAB-ON-GRADE SHALL BE SCHEDULE 40 PVC. TRANSFORM ALL PVC CONDUIT TO RIGID GALVANIZED STEEL BEFORE PENETRATING SLAB.
19. ALL UNDERGROUND CONDUIT SHALL BE WRAPPED RIGID STEEL WITH THREADED COUPLINGS AND CONNECTORS, OR PVC SCHEDULE 40. ALL ELBOWS AND EXPOSED RISERS SHALL BE RIGID STEEL CONDUIT. ALL UNDER SLAB CONDUIT SHALL BE BURIED IN SUB BASE MATERIAL AT LEAST 1". CONDUIT RUNS ARE NOT PERMITTED TO RUN IN FLOOR SLAB.
20. SWITCH GEAR AND PANEL BOARDS SHALL BE AS MANUFACTURED BY SQUARE D. ALL THREE PHASE PANEL BOARDS SHALL HAVE BOLT-IN CIRCUIT BREAKERS ONLY. ALL 120/240 VOLT CAN BE PLUG IN BREAKERS.
21. ALL CIRCUITS SHALL INCLUDE AN INSULATED GREEN GROUNDING CONDUCTOR, SIZED PER TABLE 250-95 OF NFPA 70. THIS CONDUCTOR SHALL BE CARRIED IN ALL RACEWAYS INCLUDING THOSE INSTALLED FOR SWITCH LEGS AND SHALL BE ATTACHED TO THE DEVICE, LUMINAIRE, OR EQUIPMENT HOUSING USING A SUITABLE GROUNDING LUG.
22. PROVIDE ALL ELECTRICAL SWITCH GEAR SUCH AS SWITCHBOARDS, TRANSFORMERS, MOTOR CONTROL CENTERS, PANEL BOARDS, DISCONNECT SWITCHES, ETC. WITH ENGRAVED PHENOLIC NAMEPLATES INDICATING IDENTIFICATION DESIGNATION, AND EQUIPMENT SERVED.
23. PROVIDE AND MOUNT ALL FREESTANDING ELECTRICAL EQUIPMENT SUCH AS SWITCHBOARDS, TRANSFORMERS, MOTOR CONTROL CENTERS, ETC. ON A 4" HIGH CONCRETE HOUSEKEEPING PAD.
24. PROVIDE ALL PANEL BOARDS WITH TYPED DIRECTORIES INSTALLED UNDER A CLEAR PLASTIC COVER. SUBMIT DIRECTORY INFORMATION TO THE OWNER FOR APPROVAL PRIOR TO FINALIZATION.
25. ELECTRICAL CONTRACTOR TO COORDINATE ELECTRICAL REQUIREMENTS, FOR DATA & SECURITY WITH MECHANICAL CONTRACTOR
26. PROVIDE AND INSTALL ALL JUNCTION AND PULL BOXES REQUIRED FOR THE INSTALLATION OF ELECTRICAL DEVICES AND EQUIPMENT, WHETHER OR NOT SPECIFICALLY INDICATED ON THE PLANS. SIZING OF THESE BOXES SHALL BE PER NFPA 70.
27. UPDATE THE CIRCUIT DIRECTORY IN EXISTING ELECTRICAL PANELS TO ACCURATELY REFLECT THE NEW FIELD CONDITIONS. NEW PANELS SHALL HAVE TYPED CIRCUIT DIRECTORIES REFLECTING THE CIRCUIT ARRANGEMENT ACTUALLY INSTALLED.
28. FUSE SIZES NOT CALLED OUT ON DRAWINGS SHALL BE SIZED PER NFPA 70 BY THE CONTRACTOR. IN NO CASE SHALL FUSE SIZES BE LARGER THAN IS REQUIRED BY NFPA 70.
29. ALL PENETRATIONS THROUGH FIRE RATED WALLS AND SLABS SHALL BE SEALED TO MAINTAIN THE INTEGRITY OF THE FIRE RATING USING A U.L. LISTED FIRE RATED SEALANT. 3M(PSS)7904 OR APPROVED EQUAL.
30. OBTAIN APPROVAL FROM THE ENGINEER BEFORE MAKING ANY PENETRATIONS THROUGH STRUCTURAL MEMBERS OR FIRE RATED WALLS AND SLABS.
31. SHOULD PROJECT CONDITIONS REQUIRE REARRANGEMENT OF WORK, MARK SUCH CHANGES ON THE AS-BUILT DRAWINGS. IF THESE CHANGES REQUIRE ALTERNATE METHODS TO THOSE SPECIFIED IN THE CONTRACT DOCUMENTS, SUBMIT DRAWINGS SHOWING THE PROPOSED ALTERNATE METHODS TO THE ENGINEER. DO NOT PROCEED UNTIL APPROVAL IS OBTAINED. REARRANGEMENT OF WORK FOR THE PURPOSE OF COORDINATION BETWEEN TRADES SHALL NOT BE CONSIDERED AN ITEM FOR EXTRA COST.
32. SUBMIT SHOP DRAWINGS TO THE OWNER FOR ALL LUMINARIES, EQUIPMENT AND DEVICES COVERED BY THIS CONTRACT FOR APPROVAL PRIOR TO ORDERING. SHOP DRAWINGS SHALL BEAR THE CONTRACTOR'S STAMP AND SIGNATURE INDICATING THAT THEY HAVE BEEN CHECKED FOR COMPLIANCE WITH THE CONTRACT DOCUMENTS. SHOP DRAWINGS NOT BEARING CONTRACTOR'S APPROVAL WILL BE RETURNED UNAPPROVED.
33. SERIES RATING OF UPSTREAM OR DOWNSTREAM FUSES, CIRCUIT BREAKERS, OR SWITCH GEAR IS PROHIBITED. ONLY FULLY RATED SYSTEM COMPONENTS WILL BE ACCEPTED.

REVISIONS	
1	-
2	-
3	-

ELECTRICAL GENERAL NOTES

INDUCTION METHANE
80KW COGEN
1603 HWY. 20
MARYSVILLE, CA.
95901

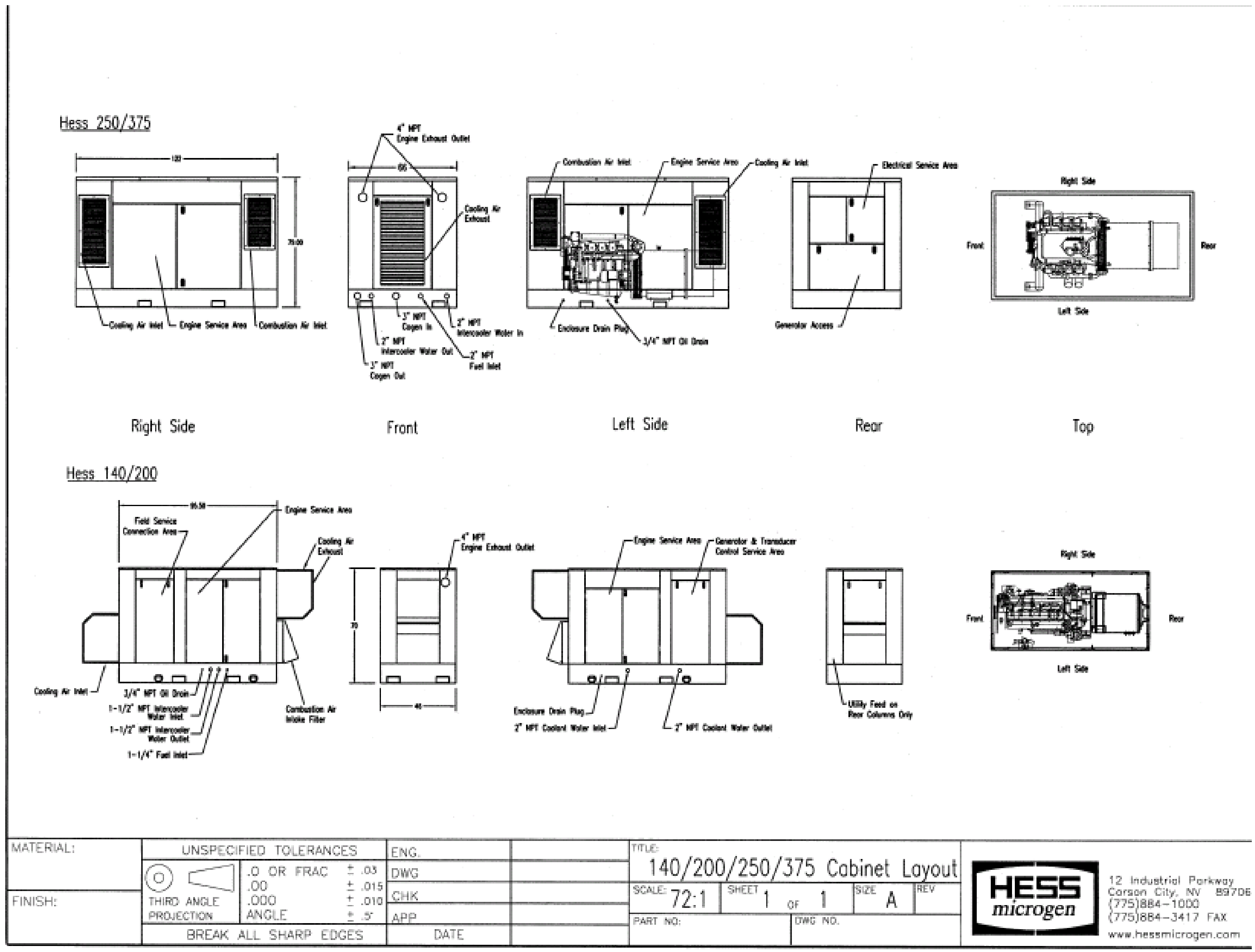
SEAL

DESIGNED BY:	Herb Clowers	DATE:	6-14-03
DRAWN BY:	bsp	DATE:	6-14-03
CHECKED BY:	Herb Clowers	DATE:	-
APPROVED BY:	-	DATE:	-
APPROVED BY:	-	DATE:	-

HESS microgen
12 INDUSTRIAL PARKWAY
CARSON CITY, NEVADA
89701
(775) 884-1000
(775) 884-0417 FAX

CLIENT NO. - | JOB NO. - | SIZE D

SCALE: NA
DWG NO. E-0 | REV. -
SHEET 1 oF 4


Hess 250/375
Right Side
Front
Left Side
Rear
Top
Cooling Air Inlet
Engine Service Area
Combustion Air Inlet
4" NPT Engine Exhaust Outlet
Cooling Air Exhaust
3" NPT Cogen In
2" NPT Intercooler Water In
2" NPT Intercooler Water Out
2" NPT Fuel Inlet
3" NPT Cogen Out
Enclosure Drain Plug
3/4" NPT Oil Drain
Electrical Service Area
Generator Access
Right Side
Left Side
Front
Rear
Hess 140/200
Field Service Connection Area
Engine Service Area
Cooling Air Exhaust
Cooling Air Inlet
3/4" NPT Oil Drain
1-1/2" NPT Intercooler Water Inlet
1-1/2" NPT Intercooler Water Outlet
1-1/4" Fuel Inlet
Combustion Air Intake Filter
4" NPT Engine Exhaust Outlet
Generator & Transducer Control Service Area
Enclosure Drain Plug
2" NPT Coolant Water Inlet
2" NPT Coolant Water Outlet
Utility Feed on Rear Columns Only
MATERIAL:
FINISH:
UNSPECIFIED TOLERANCES
THIRD ANGLE PROJECTION
.0 OR FRAC ± .03
.00 ± .015
.000 ± .010
ANGLE ± .5°
BREAK ALL SHARP EDGES
ENG.
DWG
CHK
APP
DATE
TITLE:
140/200/250/375 Cabinet Layout
SCALE: 72:1
SHEET 1 OF 1
SIZE A
REV
PART NO:
DWG NO.
HESS microgen
12 Industrial Parkway
Carson City, NV 89706
(775)884-1000
(775)884-3417 FAX
www.hessmicrogen.com

9.0 Commercialization Outlook and Technology Transfer Activities

9.1 Technical and Performance Attributes of BioHALO

As can be seen from Table 9-1, the BioHALO technology converts the least expensive, most efficient, and widely accepted prime mover for LFG to energy applications, and, with the addition of a reformer, makes it environmentally superior to today's microturbine. Meeting these goals and commercializing BioHALO will have a large environmental impact. Table 9-1 presents the annual emissions from a landfill under three operating scenarios. Scenario A is an uncontrolled landfill venting all the landfill gas and purchasing 71 kW of power from a BACT-equipped central station power plant. Scenario B has the landfill flaring its LFG and purchasing 71 kW of power. In Scenario C, the landfill has installed the BioHALO IC engine system. In Scenarios A and B, the LFG (vented or flared) emissions assume an amount of LFG equivalent to what would be consumed by a 71 kW BioHALO IC engine. Installing a 71 kW BioHALO IC engine at an uncontrolled landfill could eliminate 2,700 tons of greenhouse gas (GHG) emissions each year with only a 25 lb/yr increase in NO_x. Diverting enough flared LFG to power a 71 kW BioHALO IC engine eliminates 263 tons/yr of GHG and reduces NO_x emissions by 212 lb/yr. If 200 kW engines were installed at 100 landfills, the impact on GHG and criteria pollutant emissions would be significant.

Table 9-1. Emission Benefit of the BioHALO IC Engine for LFG to Electricity Applications

	tons/yr			lb/yr		
	CH_4	CO_2	GHG[a]	NO_x	VOC	CO
Landfill Scenario A [b]						
Vent LFG	135	614	3,444			
Purchase 71 kW		239	239	37	12	56
Total	135	853	3,683	37	12	56
Landfill Scenario B [c]						
Flared Landfill Gas	1	981	1,009	236	44	933
Purchase 71 kW	0	239	239	37	12	56
Total	1	1,220	1,248	274	56	989
Landfill Scenario C [d]						
71 kW HALO IC Engine	0	985	985	62	44	560

[a] Greenhouse Gas equal to CO_2 plus 21•CH_4 (CH_4 GWP = 21; 21 times as effective at trapping heat than CO_2).
[b] Landfill vents an amount of LFG equal to what could power a 71 kW BioHALO IC engine and purchases 71 kW from a BACT power plant.
[c] Landfill flares the same LFG as case b and purchases 71 kW from a BACT plant.
[d] Landfill installs 71 kW BioHALO IC Engine.

9.2 Economics of BioHALO

A second barrier to landfill gas to electricity projects is economics. Existing air quality regulations do not mandate conversion of the landfill gas to electricity; it simply must be combusted. For a landfill operator to undertake a landfill gas to electricity project, the avoided cost of purchased power must at least offset the cost of the annualized cost of the equipment. The simple payback period should be less than five years. Absent a mandate to install a prime mover, if it is less expensive to flare the gas, the gas will be flared. If the proposed project is successful, the installed cost for a reformer/IC engine system is estimated to be $895 per kW. This assumes limited production of the reformer system (100 units per year). The simple payback period is estimated at 2.1 years. Table 9-2 provides estimates for the annualized costs of BioHALO IC engine system and compares these to those for a commercial microturbine system. The BioHALO IC engine system has the clear cost and NOx emission advantage.

More and more landfills will be required to collect and process their gases over the next 10 years. These landfills and others that are currently flaring this resource could be enticed to convert it to electricity if the economics are attractive and the project is permittable. Successful demonstration of the authors' proposed technology will provide a low-cost, environmentally acceptable landfill gas to electricity technology option. Availability of this technology in the near term will minimize wasteful flaring of landfill gas, augment California's installed generating capacity, and reduce emissions of greenhouse gases without increasing criteria pollutant emissions. If successful demonstration of this technology does not occur within the next two to three years, the gas will continue to be flared and/or conventional lean burn IC engines will be installed.

Table 9-2. Estimated Costs for Typical LFG to Electricity Projects

71 kW LFG to Electricity Project	Units	BioHALO IC Engine	Commercial Microturbine
Total Installed Cost[a,b]	\$ \$/kW	63,510 895	138,428 1,950
Assumptions			
Lifetime Interest Rate	yrs \$	10 8	10 8
Annual Capital Cost	\$/yr	9,465	20,630
Avoided Cost of Power			
Purchase Price[c] Capacity Factor kWh Generated Cost Savings Affordability	\$/kWh % kWh \$/yr \$/kWh	0.081 80 497,568 40,303 0.0190	0.081 80 497,568 40,303 0.0415
Net Benefit	\$/yr	30,838	19,673
Simple Payback	yrs	2.1	7.0
NO_x Emissions	lb/MWh g/bhp-hr ppm (15% O_2) lb/MMBtu	0.100 0.032 x 0.01	1.72 x 25 0.116

[a] IC engine gen set capital cost = \$500/kW; Reformer = \$300 per kW H_2+CO generated plus \$1,000 for controls. Includes modules listed in the bill of materials (see Table 8-2 above), including activated carbon trap for removal of sulfur and siloxane contaminants upstream of reformer. Assume installation is 50% of capital cost.
[b] SCAQMD purchased and installed 53 Capstone 60 kW units for \$6.2 million.
[c] From PG&E medium size business tariff.

9.3 Addressable Market for BioHALO

The proposed BioHALO process development and demonstration offers California a robust near-term technology that addresses an immediate market and has ultimate addressable market potential well in excess of the longer-term, higher risk, alternative technologies. In comparison to turbine technologies, the integrated BioHALO system offers comparable emissions but at lower cost, enhanced load-following capability and improved tolerance to fuel contaminants. Compared to fuel cells, the BioHALO system offers immediate commercialization, lower risk, improved load following characteristics, and broader fuel flexibility.

It is especially important that the resultant commercialization package is a near-term, integrated and robust system because many landfills in the addressable market have been closed and are managing a gradual decline in LFG capacity. It is essential that california penetrate this market with low-cost, reliable, but clean systems before the capacity is lost.

The market will be primarily new gen-sets equipped with the BioHALO technology. The integrated package will be offered commercially by LFG engine packagers such as Gauscor, Deutz, Caterpillar, and Waukesha. They will have full responsibility for a turnkey system, including engineering, procurement, system integration, and installation. The packager will procure the autothermal reformer from Intelligent Energy or Aspen Products Group for hydrogen generation. The CHP feature, generating hot water from the waste heat, will be offered as an option. The packagers have an existing network of sales representatives and field engineers that will be mobilized for this new offering upon satisfactory demonstration of the results from the first demonstration site. This use of existing commercialization infrastructure will greatly facilitate the market penetration, reduce entry time and overhead costs, and will rely on established relationships with suppliers and customers. For the smaller retrofit market, the BioHALO configuration retrofit requirements will be highly site-specific. In these cases, the packager will sell the package through the existing sales network. The packager will perform the engineering and installation of the autothermal reformer system and will subcontract the engine modifications to the engineer/supplier for the current engine.

The BioHALO technology addresses the majority of landfill gas-to-energy opportunities identified in the 1999 EPA inventory (EPA 430-K-99-004). Specifically, landfill opportunities addressed include:

- Retrofits to current projects to reduce emissions or expand capacity (estimate addressable market at 9 sites, 77 MW).
- New BioHALO gen-set installations at candidate sites for power or CHP generation (addressable: 14 sites, 78 MW).
- Reactivation of units at shutdown sites with sustained LFG generation (addressable: 3 sites, 8 MW).
- New BioHALO gen-sets at other sites (addressable: 35 sites, 15 MW).
- New BioHALO gen-sets or retrofit to existing units at "unknown WIP" sites (addressable: 39 gen-sets, 20 MW).

The total addressable market size is 100 sites adaptable to the BioHALO technology with an aggregate generating capacity potential of 198 MW. The total capital installed cost for the addressable market is $177 million. For 20 percent capture of the addressable market and 10 percent margin, the earnings back to the BioHALO packager would be about $3.5 million.

The public benefits include:

- Displacement of central station power, or creation of new generating capacity at lower cost: Annual public savings of $12M in power costs (based on a cost savings of $0.06/kW-hr).
- Reduction in total greenhouse gas loading to the state of 0.9 million tons/ yr of CO_2 equivalent. Annual cost equivalent (at $25/ton GHG) of $22M.

- Reduction in NOx for landfills previously using higher emission IC engines or turbines, or using flaring.

Clearly, the development of the BioHALO technology shows strong commercial prospects with strong public and private benefits justifying the investment. Annual public benefits from deployment of the technology up to approximately 6 percent of the total market will exceed $30M, justifying the PIER investment. Total private earnings over the market life cycle are $3.5M, justifying the BioHALO packager investment in launching the commercial offering at the conclusion of this project and an initial field demonstration.

The emission reduction potential with BioHALO technology fully complies with the form and intent of SB 1298, and the implementation of that legislation could promote the commercial prospects of the BioHALO offering. Upon successful demonstration of the technology, the BACT for NOx from landfill and other waste gas firing will be lowered to the same level as central station NOx, rather than necessitating the higher levels accorded presently. The lower BACT level with the BioHALO technology, coupled with the lower cost and robust design, will stimulate the market for the integrated package.

10.0 Conclusions and Recommendations

A biogas-fueled engine project was undertaken to demonstrate a new hydrogen-assisted operation technology that offers significant economic and environmental advantages over conventional low-NOx engines for landfill gas to electricity applications. This innovative technology enables use of hydrogen-enriched landfill gas, produced on-site, to shift the operating point of gas engines to low NOx regimes that are otherwise not feasible. Using this technology, there is no need for a selective reduction catalyst (SCR) system, which can be quite costly and subject to siloxane poisoning. The gas engines are conventional modern engines in many respects, except they are specially fitted with an upstream fuel reformer, which produces up to 10% hydrogen in the modified landfill gas fuel mixture.

Conclusions:

- A conventional 75 kW, 10-cylinder Ford gas engine was successfully modified to operate on hydrogen-enriched landfill gas at high levels of excess air at the TIAX engine test facility, in preparation for the demonstration test. (Special engine parts and subsystems were fabricated, which made the engine hydrogen-assist ready).
- A significant number of technical advances were made, and these are summarized in this report for the benefit of future landfill gas engine development teams that undertake the commercialization of low-NOx systems for landfill-gas power production.
- Testing was conducted to optimize the BioHALO operating configuration for this engine using synthetic landfill gas and reformate gas mixed from gas cylinders,. The key conclusion is that an NOx level of 0.11 lb per megawatt-hour could be achieved with BioHALO (see summary of test points below).
- A reformer subsystem was designed to produce hydrogen from landfill gas with required heat exchangers and process controls. The design includes parts list and estimated component costs.
- The interface of the reformer to the gas engine was separately designed with required start up sequencing.
- Extended duration tests at the low NOx operating point at the TIAX test facility were conducted at energy commission request to demonstrate sustained operation,
- A path to market to commercialize the BioHALO technology was outlined, and there are no fundamental barriers perceived.

The following target performance specifications of the mature commercial embodiment of the hydrogen-assisted engine will make this technology quite competitive:

- 34-38% efficiency
- $1000/kW installed cost

- Emission levels controlled to 0.1 lb per megawatt-hour NOx
- No requirement for SCR

Based upon scoping tests in Task 2.2 and the concept optimization tests in Task 2.3, the BioHALO technology was demonstrated in the TIAX engine facility to be successful in improving the emissions performance of the engine. NOx levels of 0.11 lb per megawatt-hour were measured in sustained operation with hydrogen addition allowing 100% excess air (10% oxygen in exhaust). However, emissions levels are still slightly above the proposed goals. Following is a list of the conclusions and recommendations from the testing:

- The improved mixing provided by the intake redesign in addition to the higher amounts of hydrogen supplementation proved effective in reducing the engine emissions.
- The ignition system, when switched to high-energy options, did not show a particular improvement in performance or emissions. A further concern noted during this task was that even though ignition was achieved of the mixture, the burn times are slightly longer than desirable, leading to cycle-to-cycle variability.
- Water injection was interesting in that it allowed for lower NOx emissions when compared to a standard point of similar dilution but did not improve the emissions to the point beyond emissions targets.
- Although NOx targets were not met, the results show an impressive emissions reduction for a reciprocating engine technology. For example, BACT for a Hess Microgen stoichiometric natural gas engine with a three -way catalyst is 0.07 g/bhp-hr, and this project demonstrated multiple points 50-67% of this value *engine out.*

The Task 2.2 scoping tests showed the ability of BioHALO technology to achieve a significant 93% reduction in the NOx emissions levels using reformate, when compared to the NOx at the leanest operating condition without reformate addition. However, the project target of 0.032 g/bhp-hr NOx (0.1 lb per megawatt-hour) was not met, and reaching this target would require an additional 75% NOx reduction. In the Task 2.2 tests, the lean limit of operation reached was 8% O_2 and the engine would not run at acceptable COV at the lean conditions (beyond 8% O_2 in the exhaust) needed to reach the 0.1 lb per megawatt-hour NOx level.

A summary of the lowest NOx points obtained in Task 2.3, which still provided acceptable combustion stability is shown below in Table 10-1 .

Table 10-1. Summary of low NOx points with acceptable combustion stability

IMEP (bar)	IMEP COV (%)	NOx (Corrected to 15 % O_2) [ppm]	NOx (g/bhp hr, 15% O_2)	H_2 LHV/CH_4 LHV	NOx (lb/MW hr), 15 % O_2
5.4	8.1	5	0.035	13.5%	0.10
6.9	11.0	7	0.044	11.4%	0.13
6.6	8.7	10	0.071	7.5%	0.21
6.8	12.4	9	0.078	14.7%	0.23
N/A	N/A	4	0.043	14.2%	0.13
6.1	8.7	8	0.044	10.7%	0.13
5.9	3.7	7	0.047	14.7%	0.14
6.6	8.7	10	0.071	7.5%	0.21

The NOx results as summarized in the above table show a significant reduction when compared to the results obtained in Task 2.2; so the methods of further NOx reduction suggested in the Task 2.2 test report were effective. The results do come close to the project goals 0.032 g/bhp-hr or 0.07 lb/MW-hr but are still above those goals.

Recommendations:

- It would be interesting to explore using hydrogen supplementation as an enabler for high load/high dilution pre-mixed charge ignition concepts. The hydrogen supplementation was able to light off, but work could be done to improve its combustion stability as well as improve burn durations. Using a high-energy micro-pilot or compression ignition might answer the two concerns raised in this task and provide the dilution necessary for even lower NOx.

- Because this was a test plan designed to encompass a range of operating conditions, each point was short to finish all of the testing required in the given amount of time. To prove the value of the system, it would be desirable to run for a much longer period.

- A commercial partner should be identified to provide needed matching funds (and host landfill gas site) to build the field installation and to operate the landfill gas engine facility on actual landfill gas as opposed to synthetic simulated gas.

- An actual reformer should be fabricated and demonstrated as part of BioHALO rather than use synthetic bottled gas reformate as was done here.

11.0 Glossary

A	Humidity coefficient
ATR	Auto-thermal reformer
B	Temperature coefficient
BioHALO	Biogas Hydrogen-Assisted Lean Operation
C	Carbon
CEM	Continuous Emissions Monitoring
CID	Cubic inches of displacement
CO	Carbon monoxide
CO_2	Carbon dioxide
COV	Coefficient of variation
ECU	Engine control unit
EGR	Exhaust gas recirculation
Fb	Spindt constant
Fc	Spindt fuel constant
H	Specific humidity
H(2)	Hydrogen
IC(E)	Internal combustion (engine)
IMEP	Indicated mean effective pressure
K	Dimensionless correction factor
LFG	Landfill gas
LHV	Lower heating value
LNV	Least normalized value
O_2	Oxygen
Pb	Barometric pressure
Pv	Partial pressure of water
PWM	Pulse width modulated
Q	O_2/CO_2 ratio
R	CO/CO_2 ratio
RH	Relative humidity
RPM	Revolutions per minute
T	Temperature
T/C	Thermocouple
TTL	Transistor type logic
Y	H/C mass fraction
NOx	Oxides of nitrogen
η_{fi}	Indicated fuel conversion efficiency

APPENDIX A. COMPLETE DATA SET

Equations Used FOR Emissions Data Conversion

Since NOx formation is affected by humidity at the test site, a correction will be made using the following expression [1]:

$$NOxcorr = \frac{NOx}{K} \tag{A1}$$

NOx has units of ppm, and K (a dimensionless correction factor) is defined as follows:

$$K = 1 + 7 * A(H - 10.714) + 1.8B(T - 29.44)) \tag{A2}$$

A in the above equation is:

$$A = 0.044\left(\frac{Fuel}{Air}\right) - 0.0038 \tag{A3}$$

The fuel-air-ratio is on a dry mass basis, and is dimensionless for both equations A3 and A4:

The variable B from equation A2 is:

$$B = -0.116\left(\frac{Fuel}{Air}\right) + 0.0053 \tag{A4}$$

T is the intake temperature in deg C, and H is defined as:

$$H = \frac{621.98Pv}{Pb - Pv} \tag{A5}$$

Pv is the partial pressure of the water vapor in in Hg, and Pb is the barometric pressure in in Hg. Since during the test dry bulb temperature and relative humidity (in percent) were recorded, Pv may be calculated from equation A6:

$$Pv = RH\left(Pd\right) \tag{A6}$$

Pd is calculated from the following equation:

$$\begin{aligned} Pd &= -4.14438x10^{-3} + 5.76645x10^{-3}T - 6.32788x10^{-5}T^2 \\ &+ 2.12294x10^{-6}T^3 - 7.85415x10^{-9}T^4 + 6.55263x10^{-11}T^5 \end{aligned} \tag{A7}$$

Where T is Temperature in deg F, and the equation is valid from 20 to 110°F.

The relative air/fuel ratio is calculated using the well-accepted Spindt method from the engine exhaust constituents as measured by the emissions bench. The Spindt equation is shown below [2]:

$$Fb * (11.492 * Fc * ((1 + 0.5 * R + Q)/(1 + R))) + ((120 * (1 - Fc))/(3.5 + R))) \tag{A8}$$

Fb is defined as:

$$(CO_2 + CO)/(CO_2 + CO + (0.001 * THC)) \quad \text{(A9)}$$

Where CO_2 and CO are in volume percent, and THC is in ppm.

Fc is defined as:

$$12.01/(12.01 + 1.008 * Y) \quad \text{(A10)}$$

Where Y is the H/C mass ratio of the fuel being used during the test. R is the ratio of CO to CO_2, and Q is the ratio of O_2 to CO_2, all on a dry volume basis.

Indicated Power in kW was calculated from the IMEP (kPa) by the following expression:

$$P = \frac{IMEP(V_d)(N)}{1000 n_r} \quad \text{(A11)}$$

Where Vd is the engine displaced volume in dm3, N is the number of revolution per second, and nr is 2 for a four-stroke engine.

Brake Power was calculated given the electrical power output and the generator efficiency as shown on the Marathon generator specification sheet. Table A-1 shows the Marathon generator efficiency:

Table A-1. Marathon Generator Conversion Efficiency

Electrical Power (kW)	Efficiency
40	94%
60	93%
80	92%

The indicated specific fuel consumption is calculated by dividing the fuel flowrate by the indicated power.

The fuel conversion efficiency is calculated as:

$$\eta_{fi} = \frac{P}{\dot{m}_f Q_{LHV}} \quad \text{(A12)}$$

Where P is the power as calculated above in Watts, mf is the fuel flow rate in kg/s, and QLHV is the Lower Heating Value of the fuel in J/kg. For the fuel conversion efficiencies shown here, hydrogen was included as a fuel, with a LHV = 120 MJ/kg, and natural gas with a LHV = 45 MJ/kg.

The specific emissions were calculated using the following formula:

$$\left[\frac{g}{kW - hr}\right] = \frac{0.062(exh)(NOx)}{P} \quad \text{(A13)}$$

Where *exh* is the exhaust mass flow rate in kg/min, NO_x has units of ppm, and Power is in kW, and due to the conservation of mass, includes the air, fuel, CO_2, N_2, and reformate ingested into the engine [1].

NOx is corrected to 15% O_2 in the exhaust using the following expression:

$$NO_x\left(15\%O_2\right)=\frac{5.9}{20.9-O_2}NOx \quad \text{(A14)}$$

Where O_2 is the measured dry concentration of oxygen in percent, and NO_x is the dry measured concentration of NO_x in ppm [3].

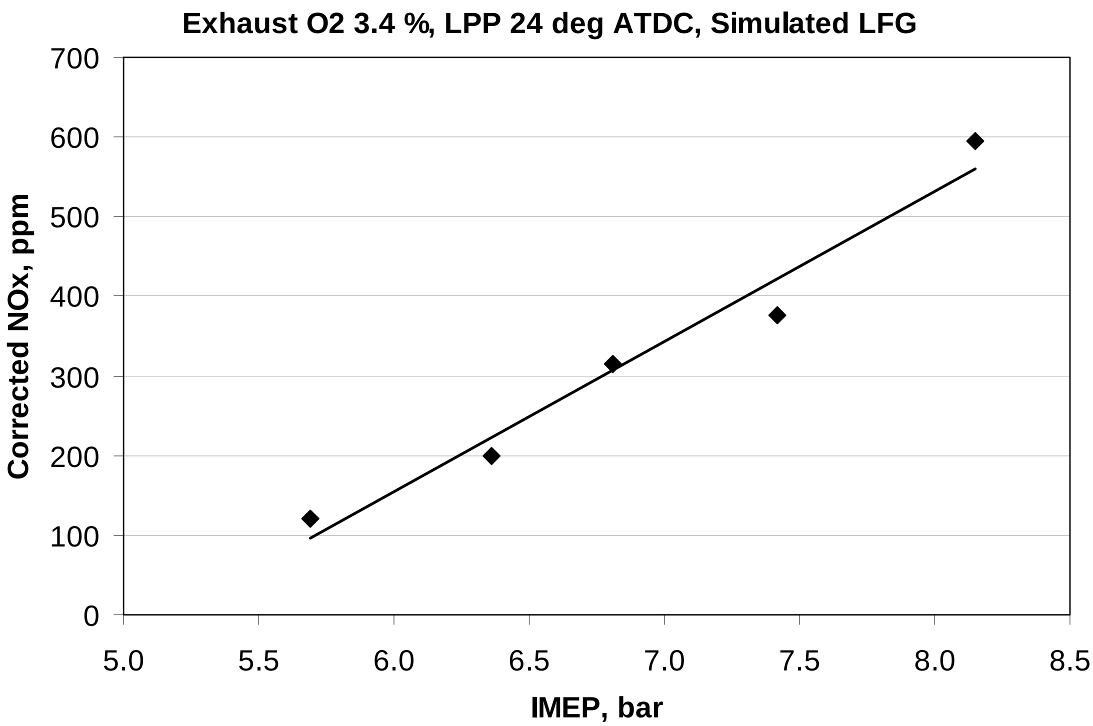
References:

1. SAE J177 Jun95: "Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust."

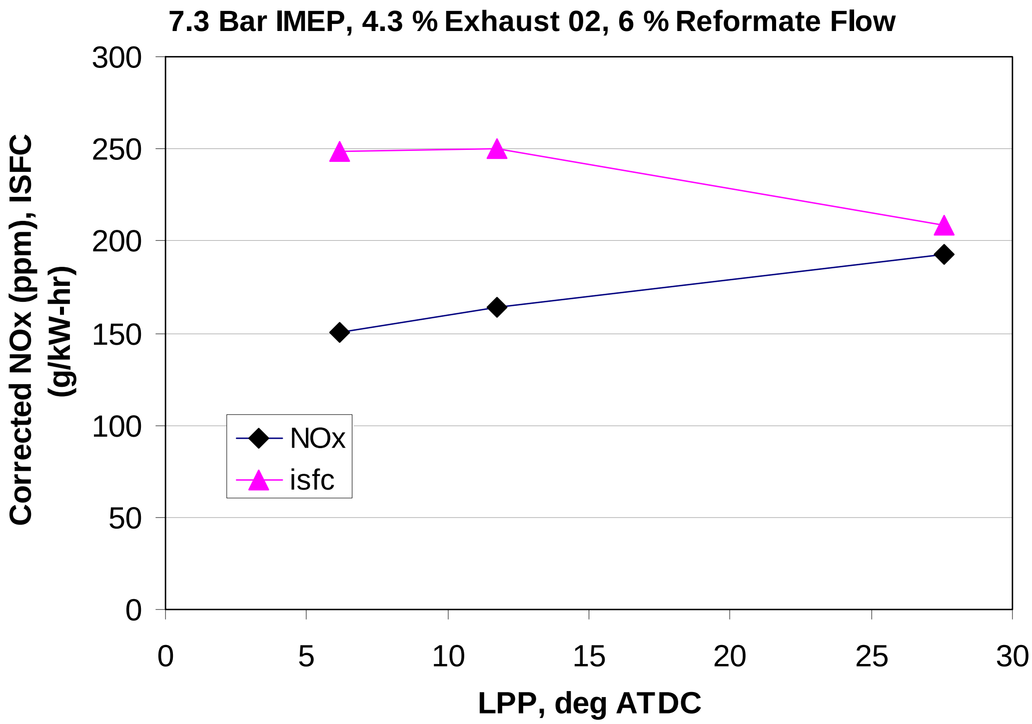
2. Spindt, R.S., 1965, "Air-Fuel Ratios from Exhaust Gas Analyzer," SAE Paper No. 650507.

3. Method 20: Determination of Nitrogen Oxides, Sulfur Dioxide and Diluent Emissions from Stationary Gas Turbines. State of California Air Resources Board. Adopted: March 28, 1986 Amended: July 1, 1999.

Complete Data Set and Supplemental Data



The above graph shows a sweep of IMEP while holding a fixed air/fuel ratio and LPP. The lower in-cylinder temperatures at the lower IMEP lead to less NOx production.



*

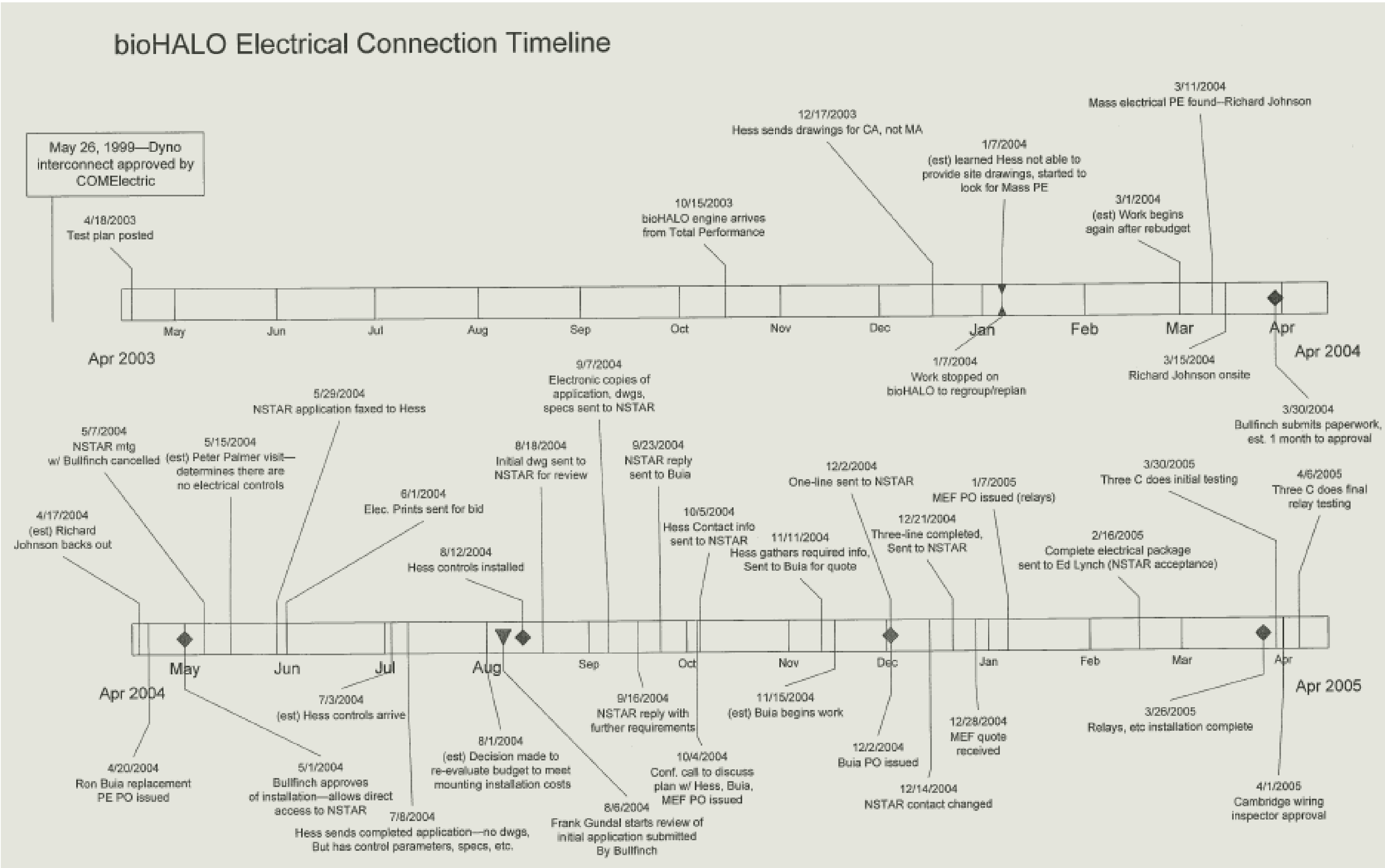
This Figure shows the effect of spark retard on NOx production. Spark retard lowers the in-cylinder temperature, but there is a fuel economy loss, as shown by the ISFC values.

Table A-2: Summary of Test Results

Date	Indicated Power (kW)	isfc (g/kW hr)	isfc (lbm/hp hr)	Indicated Fuel Conv. Eff.	IMEP (bar)	COV %	LNV %	LPP (deg)	1090 (deg)	FFR (g/s)	%O2	Hum. corr Nox	NOx g/ ihp-hour	NOx g/bhp hour	NOx lb/MW hr	15% O2 Corr. Nox
5-Aug-05	85	228	0.37	35%	8.3	1.4	95.8	20	29.75	5.36	2.5	2722	9.47	11.67	34.50	903
5-Aug-05	81	262	0.43	30%	7.9	4.5	82.6	24	38.00	5.88	4.2	298	1.23	1.53	4.52	112
5-Aug-05	81	212	0.35	38%	7.9	15.4	-1.7	18	37.00	4.77	5.5	436	1.78	2.21	6.53	182
6-Sep-05	79	220	0.36	36%	7.8	1.5	94.3	19.74	32.92	4.84	1.6	2457	8.29	10.31	30.48	767
6-Sep-05	71	203	0.33	39%	7.0	7.1	64.7	18.32	39.85	4.01	7.3	48	0.25	0.31	.92	23
5-Aug-05	79	235	0.39	34%	7.7	5.1	78.0	21	39.00	5.11	5.8	102	0.49	0.61	1.80	44
5-Aug-05	86	200	0.33	39%	8.5	1.9	92.8	23	33.00	4.76	3.1	728	2.67	3.28	9.70	252
5-Aug-05	80	230	0.38	34%	7.8	4.5	79.0	23	37.00	5.06	7.4	110	0.53	0.66	1.95	55
5-Aug-05	78	215	0.35	37%	7.7	3.1	86.7	25	36.00	4.64	3.5	352	1.34	1.68	4.97	125
5-Aug-05	65	255	0.42	31%	6.4	38.0	-2.4	14	41.00	4.59	7.9	69	0.37	0.48	1.42	36
5-Aug-05	82	210	0.35	37%	8.1	2.1	91.0	23	33.00	4.72	5.1	307	1.26	1.56	4.61	124
5-Aug-05	75	213	0.35	36%	7.4	3.6	87.0	23	37.00	4.35	6.7	62	0.28	0.36	1.06	29
5-Aug-05	61	263	0.43	30%	6.0	18.0	1.2	4.85	49.00	4.35	8.1	21	0.12	0.16	.47	11
9-Aug-05	52	294	0.48	26%	5.1	62.0	-2.4	10.12	41.22	4.20	8.5	81	0.58	0.78	2.31	45
5-Aug-05	68	261	0.43	30%	6.7	12.3	9.8	1.7	47.00	4.85	7.2	23	0.15	0.20	.59	11
5-Aug-05	70	247	0.41	31%	6.9	8.2	64.0	2.8	45.00	4.70	7.6	20	0.12	0.15	.44	10
9-Aug-05	67	240	0.39	32%	6.6	30.4	-1.6	13.34	43.88	4.36	8.2	48	0.29	0.38	1.12	26
5-Aug-05	83	201	0.33	38%	8.1	1.7	94.0	22	31.00	4.52	5.3	280	1.14	1.41	4.17	115
6-Sep-05	87	231	0.38	33%	8.6	2.6	89.3	24.85	32.34	5.45	3.3	569	2.35	2.88	8.51	200
5-Aug-05	70	203	0.33	38%	6.8	4.8	57.0	21	39.00	3.83	7.6	31	0.15	0.19	.56	16
9-Aug-05	83	189	0.31	40%	8.2	3.0	84.7	18.59	33.35	4.23	7.3	133	0.65	0.81	2.39	65
9-Aug-05	78	196	0.32	39%	7.6	2.6	89.4	23.03	33.52	4.08	6.3	99	0.49	0.61	1.80	44
9-Aug-05	73	204	0.34	37%	7.1	6.3	35.8	20.08	38.74	3.97	7.8	34	0.16	0.20	.59	17
6-Sep-05	75	193	0.32	39%	7.3	4.3	86.6	22.09	35.36	3.85	7.2	63	0.30	0.38	1.12	31
6-Sep-05	33	397	0.65	19%	3.3	50.4	-4.6	1.07	58.16	3.50	11.1	4	0.04	0.06	.18	3
6-Sep-05	71	184	0.30	41%	7.0	2.3	86.2	22.91	32.79	3.47	6.2	113	0.52	0.66	1.95	50
6-Sep-05	47	210	0.35	35%	4.6	28.7	-1.9	5.67	53.21	2.62	8.9	10	0.06	0.09	.27	6
6-Sep-05	43	290	0.48	26%	4.2	45.6	-3.4	2.73	53.05	3.29	9.5	7	0.05	0.08	.24	4

Task 2.3 Conceptual Process Optimization Data Points

date	time	Test Set	Water flow (g/s) or EGR Value	Intake Air Temperaure (deg C)	Brake Power (kW)	Air (kg/s)	MAP (kPa)	CH4 flow (kg/s)	IMEP (bar)	IMEP COV (%)	10-90 burn (CAD)	Humidity Corr NOx (ppm)	NOx (15% O2)	NOx (g/bhp hr @ 15%)	THC (ppm)	Dry CO2 (%)	Dry O2 (%)	Dry CO (%)	NOx COV (%)	H2 Suppl. (%LHV)	Brake Efficiency	NOx (lb/MW-hour)
18-Jan-07	11:42	2		60	41	0.10	110	0.003	5.4	8.1	46.74	8	5	0.035	6922	6.1	10.9	0.01	2.70	13.5%	30%	0.10
24-Jan-07	16:31	2		58	48	0.13	110	0.004	6.2	27.0	44.67	11	6	0.048	1895	7.5	9.7	0.06	14.30	11.3%	26%	0.14
24-Jan-07	16:35	2		55	46	0.14	110	0.004	5.9	39.0	44.86	8	5	0.044	4158	7.0	10.5	0.07	29.70	12.5%	25%	0.13
25-Jan-07	13:56	2		59	57	0.11	117	0.004	7.1	4.7	35.08	68	31	0.190	613	8.7	8.1	0.04	41.70	9.5%	32%	0.56
25-Jan-07	14:05	2		62	61	0.11	121	0.004	7.5	1.7	31.08	94	46	0.247	526	6.1	8.8	0.03	7.90	9.5%	36%	0.73
25-Jan-07	14:18	2		69	56	0.11	121	0.004	6.9	11.0		14	7	0.044	1002	7.2	9.2	0.05	3.20	11.4%	33%	0.13
25-Jan-07	14:23	2		66	36	0.12	125	0.003	4.9	15.8	51.55	8	4	0.040	1086	7.3	9.2	0.05	6.00	12.1%	22%	0.12
25-Jan-07	15:56	2		59	55	0.11	116	0.004	6.9	4.2	35.98	42	20	0.123	761	8.0	8.7	0.04	9.10	9.1%	34%	0.36
25-Jan-07	15:59	2		60	43	0.11	115	0.003	5.6	18.3	46.48	13	7	0.051	2052	9.2	9.1	0.06	11.70	9.2%	27%	0.15
25-Jan-07	16:02	2		61	54	0.11	113	0.003	6.8	4.0	33.69	65	32	0.186	648	5.9	9.1	0.04	23.70	9.0%	34%	0.55
25-Jan-07	16:04	2		61	57	0.11	113	0.003	7.1	5.3	33.28	61	30	0.166	709	6.0	8.9	0.04	46.00	8.9%	36%	0.49
25-Jan-07	16:08	2		64	47	0.12	125	0.004	6.0	17.3	45.04	14	7	0.053	1655	5.6	9.7	0.06	11.10	8.4%	28%	0.16
25-Jan-07	16:21	2		67	53	0.12	130	0.004	6.6	8.7	42.87	21	10	0.071	1064	6.1	9.1	0.05	15.00	7.5%	29%	0.21
31-Jan-07	15:48	2		54	45	0.13	105	0.004	5.8	40.0	39.7	99	33	0.277	1285	9.1	4.7	0.04	17.40	0.0%	24%	0.00
31-Jan-07	15:45	3		53	62	0.12	100	0.004	7.6	12.8	30.38	824	279	1.583	327	10.2	3.5	0.03	6.80	0.0%	31%	4.68
31-Jan-07	16:10	3		50	55	0.12	100	0.004	6.8	16.6	32.02	137	60	0.387	719	8.6	7.3	0.03	11.40	7.4%	31%	1.14
31-Jan-07	16:15	3		53	64	0.13	110	0.004	7.8	10.3	29.92	257	109	0.684	549	8.7	7.0	0.03	18.32	8.5%	34%	2.02
31-Jan-07	16:19	3		53	33	0.17	130	0.004	4.5	80.2	33.1	18	9	0.139	4598	7.3	9.4	0.06	11.37	7.8%	17%	0.41
31-Jan-07	16:28	3		54	70	0.16	130	0.004	8.5	14.2	29.95	111	53	0.354	919	8.1	8.5	0.03	13.60	11.0%	38%	1.05
31-Jan-07	16:33	3		53	55	0.16	128	0.003	6.8	34.9	35.79	39	19	0.169	2341	7.8	9.2	0.05	22.08	13.1%	37%	0.50
31-Jan-07	17:46	3		52	24	0.16	123	0.004	3.6	76.0	39	6	4	0.071	6420	6.3	11.0	0.12	6.70	14.1%	14%	0.21
31-Jan-07	17:49	3		53	49	0.16	123	0.004	6.2	27.8	40.27	13	7	0.066	2399	7.0	10.0	0.08	10.70	14.4%	29%	0.20
31-Jan-07	17:52	3		53	55	0.15	121	0.004	6.8	12.4	37.65	18	9	0.078	1890	7.0	10.0	0.06	5.90	14.7%	33%	0.23
31-Jan-07	17:55	3		53	49	0.15	123	0.004	6.2	25.3	39.99	11	6	0.058	2792	6.8	10.3	0.08	4.70	14.7%	30%	0.17
1-Feb-07	11:05	3		49	61	0.11	100	0.004	7.5	1.6	25.8	535	229	1.288	474	8.5	7.1	0.03	19.70	11.8%	35%	3.81
1-Feb-07	11:11	3		51	28	0.16	126	0.004	4.0	81.4	36.7	12	7	0.111	7721	6.4	10.5	0.09	7.90	9.6%	15%	0.33
1-Feb-07	11:16	3		53	64	0.17	130	0.004	7.8	24.8	34.2	65	31	0.235	1295	7.8	8.4	0.04	23.00	10.3%	33%	0.69
27-Feb-07	10:48	3		N/A	54	0.09	105	0.004	N/A	N/A	N/A	3707	1265	6.217	262	9.7	3.6	0.04	1.10	0.0%	30%	18.38
27-Feb-07	10:52	3		N/A	52	0.09	105	0.004	N/A	N/A	N/A	636	238	1.297	462	10.2	5.1	0.03	14.70	0.0%	29%	3.84
27-Feb-07	10:56	3		N/A	59	0.11	105	0.003	N/A	N/A	N/A	181	78	0.448	497	8.4	7.3	0.03	17.80	9.0%	36%	1.32
27-Feb-07	10:58	3		N/A	40	0.11	105	0.003	N/A	N/A	N/A	13	7	0.058	4074	7.0	9.7	0.07	13.50	11.0%	25%	0.17
27-Feb-07	11:01	3		N/A	36	0.15	105	0.003	N/A	N/A	N/A	7	4	0.053	8651	6.0	11.1	0.10	6.50	13.5%	22%	0.16
27-Feb-07	11:03	3		N/A	46	0.15	105	0.003	N/A	N/A	N/A	8	4	0.043	5291	6.4	10.4	0.09	8.20	14.2%	28%	0.13
10-Jan-07	14:49	4	8%	70	59	0.09	105	0.004	7.3	5.8	32.4	36		0.000	838	4.2	16.3	0.01	9.50	8.9%	36%	0.00
16-Jan-07	15:55	4		49	48	0.09	108	0.003	6.1	8.7	37.13	15	8	0.044	2267	7.8	9.5	0.07	29.00	10.7%	32%	0.13
16-Jan-07	16:02	4	8%	87	46	0.10	110	0.003	5.9	5.1	37.55	41	19	0.122	1059	8.1	8.1	0.05	53.00	15.5%	35%	0.36
16-Jan-07	16:13	4	9%	58	46	0.10	110	0.003	5.9	3.7	37.42	14	7	0.047	1337	7.2	9.7	0.06	22.10	14.7%	36%	0.14
18-Jan-07	11:33	4	31%	86	46	0.10	110	0.003	5.96	1.7	35.42	34	16	0.100	2007	7.8	8.0	0.05	88.00	14.7%	36%	0.30
30-Jan-07	15:52	4		90	54	0.15	123	0.004	6.8	13.5	39.86	36	16	0.130	1537	8.7	7.6	0.04	6.20	9.4%	28%	0.39
1-Feb-07	14:36	4	9%	56	63	0.17	120	0.004	7.7	16.4	35.3	56	24	0.191	1094	9.5	7.4	0.04	14.70	10.5%	33%	0.56
1-Feb-07	14:44	4	12%	55	40	0.17	125	0.004	0.0	7080.7	3.6	13	7	0.089	10721	7.2	10.2	0.07	12.20	10.6%	21%	0.26
14-Feb-07	14:12	4		55	56	0.09	96	0.003	N/A	N/A	N/A	56	25	0.133	N/A	8.2	8.0	0.03	11.40	13.5%	34%	0.39
14-Feb-07	14:24	4	18%	105	52	0.08	94	0.003	N/A	N/A	N/A	57	22	0.114	N/A	9.7	5.8	0.03	23.60	13.5%	34%	0.34
27-Feb-07	11:12	4	8%	N/A	45	0.15	105	0.004	N/A	N/A	N/A	317	122	1.232	365	9.5	5.6	0.03	5.00	9.7%	26%	3.64
27-Feb-07	11:16	4	14%	N/A	63	0.10	105	0.004	N/A	N/A	N/A	299	105	0.503	367	10.4	4.1	0.03	6.70	9.7%	37%	1.49
27-Feb-07	11:20	4	23%	N/A	49	0.14	105	0.004	N/A	N/A	N/A	42	13	0.118	2171	11.4	2.5	0.14	5.00	9.7%	29%	0.35
25-Jan-07	16:04:00	5	3	61	57	0.11	113	0.003	7.1	5.3	33.3	61	30	0.166	709	6.0	8.9	0.04	46	8.9%	36%	0.49
25-Jan-07	16:08:00	5	1	61	47	0.12	125	0.003	6.0	17.3	45.0	14	7	0.053	1655	5.6	9.7	0.06	11.1	8.5%	29%	0.16
25-Jan-07	16:21:00	5	1	67	53	0.12	130	0.004	6.6	8.7	42.9	21	10	0.071	1064	6.1	9.0	0.05	15.1%	7.5%	29%	0.21
Extended Run				N/A	55	0.12	120	0.003	N/A	N/A	N/A	10.6	6	.042	1900	6.9	9.4	0.06	23%	12%	31%	0.12


bioHALO Electrical Connection Timeline
May 26, 1999—Dyno interconnect approved by COMElectric
4/18/2003
Test plan posted
10/15/2003
bioHALO engine arrives from Total Performance
12/17/2003
Hess sends drawings for CA, not MA
1/7/2004
(est) learned Hess not able to provide site drawings, started to look for Mass PE
3/1/2004
(est) Work begins again after rebudget
3/11/2004
Mass electrical PE found—Richard Johnson
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
Apr 2003
Apr 2004
1/7/2004
Work stopped on bioHALO to regroup/replan
3/15/2004
Richard Johnson onsite
3/30/2004
Bullfinch submits paperwork, est. 1 month to approval
4/17/2004
(est) Richard Johnson backs out
5/7/2004
NSTAR mtg w/ Bullfinch cancelled
5/15/2004
(est) Peter Palmer visit—determines there are no electrical controls
5/29/2004
NSTAR application faxed to Hess
6/1/2004
Elec. Prints sent for bid
8/12/2004
Hess controls installed
8/18/2004
Initial dwg sent to NSTAR for review
9/7/2004
Electronic copies of application, dwgs, specs sent to NSTAR
9/23/2004
NSTAR reply sent to Buia
10/5/2004
Hess Contact info sent to NSTAR
11/11/2004
Hess gathers required info, Sent to Buia for quote
12/2/2004
One-line sent to NSTAR
12/21/2004
Three-line completed, Sent to NSTAR
1/7/2005
MEF PO issued (relays)
2/16/2005
Complete electrical package sent to Ed Lynch (NSTAR acceptance)
3/30/2005
Three C does initial testing
4/6/2005
Three C does final relay testing
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
Apr 2004
Apr 2005
4/20/2004
Ron Buia replacement PE PO issued
5/1/2004
Bullfinch approves of installation—allows direct access to NSTAR
7/3/2004
(est) Hess controls arrive
7/8/2004
Hess sends completed application—no dwgs, But has control parameters, specs, etc.
8/1/2004
(est) Decision made to re-evaluate budget to meet mounting installation costs
8/6/2004
Frank Gundal starts review of initial application submitted By Bullfinch
9/16/2004
NSTAR reply with further requirements
10/4/2004
Conf. call to discuss plan w/ Hess, Buia, MEF PO issued
11/15/2004
(est) Buia begins work
12/2/2004
Buia PO issued
12/14/2004
NSTAR contact changed
12/28/2004
MEF quote received
3/26/2005
Relays, etc installation complete
4/1/2005
Cambridge wiring inspector approval